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Cumulative Impact Analysis of Wetlands Using Hydrologic Indices

by John M. Nestler, Katherine S. Long

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	Task		Task
CP	Critical Processes	RE	Restoration & Establishment
DE	Delineation & Evaluation	SM	Stewardship & Management

Wetlands Research Program

Technical Report WRP-SM-3
September 1994

Cumulative Impact Analysis of Wetlands Using Hydrologic Indices

by John M. Nestler, Katherine S. Long

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Final report

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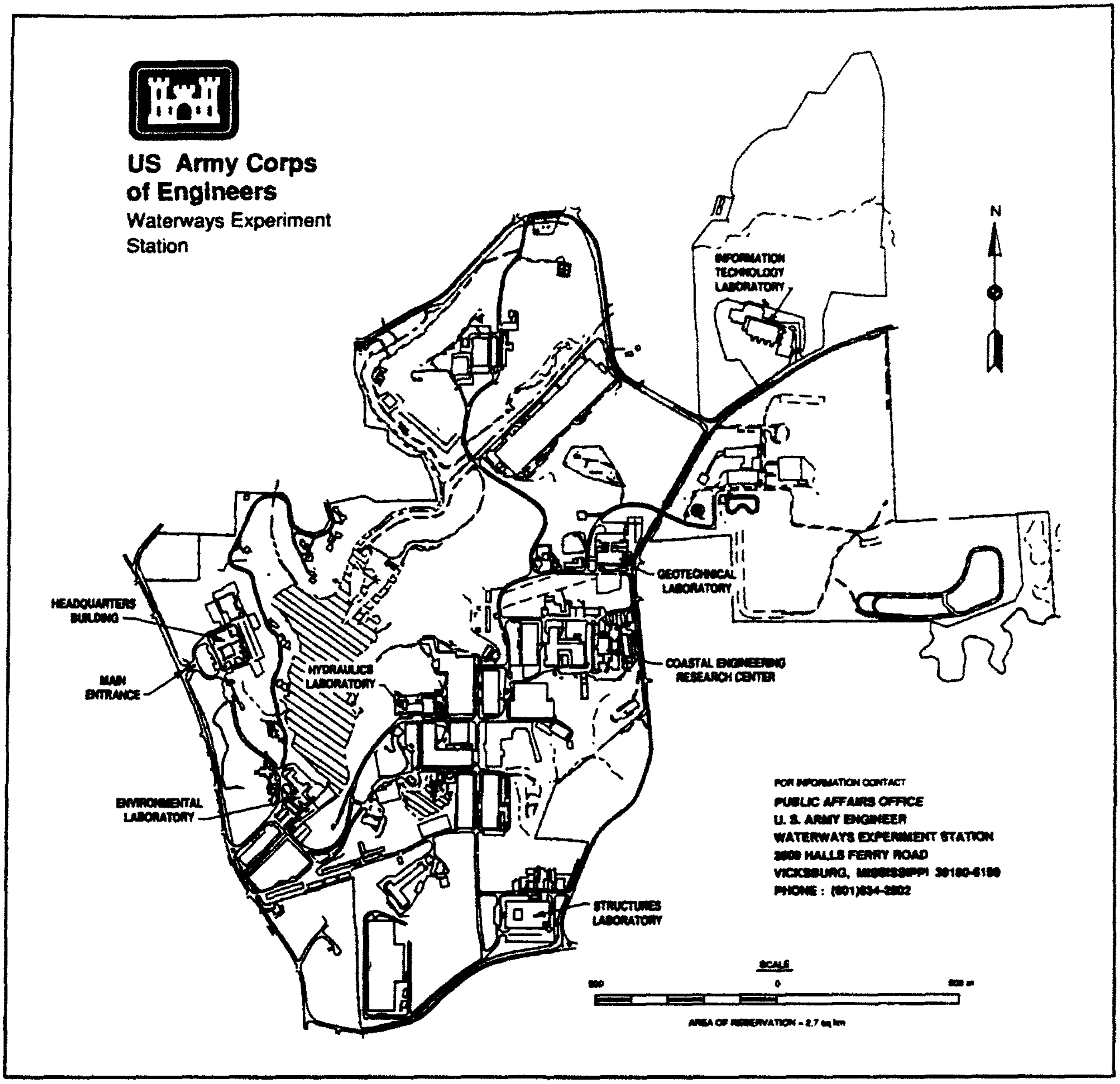

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Wetlands: Impact Assessment

Cumulative Impact Analysis of Wetlands: Hydrologic Indices (TR WRP-SM-3)

ISSUE:

In order to make informed decisions concerning cumulative impact analysis of wetlands, the Corps of Engineers Districts and other wetlands professionals need data often not directly available. Cumulative impact assessment of wetlands includes relating historic patterns of flow, derived from the stream's flow record, to changes in the watershed associated with that stream. Harmonic analysis and time-scale analysis were applied to selected stream records to ascertain their potential for describing cumulative impacts.

RESEARCH:

The study area chosen included selected streams in the White River basin, Arkansas/Missouri. The Cache River received particular emphasis because a significant amount of information was readily available concerning it and its surroundings. Daily flow values were retrieved from each of the streams. Using nonlinear, harmonic analysis as well as time-scale analysis (a technique adapted from fractal geometry) to reveal the time-dependent patterns in the respective samples, the results were compared decade-by-decade to discern changes in the historic, seasonal patterns. Other streams in the White River basin were analyzed in the same manner and compared with the Cache River, noting historic changes in land use and stream regulation.

SUMMARY:

The study identifies methods with the potential to differentiate historic time frames in which disruptions were likely to have occurred. The methods appear to be translatable to other geographic areas where streamflow is typically seasonal.

AVAILABILITY OF REPORT:

The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, or telephone (601) 634-2355.

To purchase a copy, call National Technical Information Service (NTIS) at (703) 487-4650. For help in identifying a title for sale, call (703) 487-4780. NTIS report numbers may also be requested from the WES librarians.

About the Authors:

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Contents

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Stewardship and Management Task Area of the Wetlands Research Program (WRP). The work was performed under Work Unit 32757, Cumulative Impact Analysis, for which Dr. John M. Nestler, Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station WES, was the Principal Investigator. Mr. Sam Collinson (CECW-OR) was the WRP Technical Monitor for this work.

Mr. David Mathis (CERD-C) was the WRP Coordinator at the Directorate of Research and Development, HQUSACE; Dr. William L. Klesch (CECW-PO) served as the WRP Technical Monitors' Representative; Dr. Russell F. Theriot, WES, was the Wetlands Program Manager. Mr. Chester O. Martin, WES, was the Task Area Manager.

Participants in the study, in addition to the authors, included Mr. Daniel Thompson, who provided assistance in the collection and processing of the historical data, and Drs. L. Jean O'Neil, Dara Wilber, and Mr. Bob Tighe who provided insight through discussion of their work pertaining to this effort and who offered critical review and suggestions regarding inclusion of other locations to analyze in draft versions of this report. This report was written by Dr. Nestler, Water Quality Modeling Branch (WQMB), Ecosystem Processes and Effects Division (EPED), EL, and Ms. Katherine S. Long, EPEB, under the direct supervision of Dr. Mark Dortch, Chief, WQMB, Dr. Richard E. Price, Acting Chief, EPEB, and Mr. Donald Robey, Chief, EPED, and under the general supervision of Dr. John Keeley, Assistant Director, EL, and Dr. John Harrison, Director, EL.

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1 Introduction

Background

The accumulated effect of many individual development activities, none of which is large or damaging by itself, may collectively produce major changes in wetlands functions, thereby degrading environmental quality. The importance of cumulative impacts on wetlands integrity is well-documented and is great enough that the National Environmental Policy Act requires that the Corps of Engineers (CE) and other agencies having a regulatory or stewardship responsibility for wetlands consider cumulative impacts in their environmental assessments of wetlands. Synergistic effects of several different individual impacts may collectively produce a different impact from the sum of the individual impacts (Stakhiv 1988; Granholm et al. 1988; Gosselink et al. 1990; Sumner 1991; Leibowitz et al. 1992; Davies 1991; Spaling and Smit 1993).

Cumulative-impact assessments and single-impact assessments of wetlands differ. Single impact assessments usually focus on a specific activity that affect wetlands, such as draining, filling, or channelization, with the specific nature of the impact helping to direct and to focus the activities of regulatory and stewardship agencies. In contrast, cumulative impact assessment of wetland integrity is more difficult because the many impacts that have accumulated to characterize the present state of a wetland may be widely dispersed over many decades, occur throughout a river basin, and often are difficult to define or characterize because necessary data on present and historical land use or water use practices are lacking (Cocklin, Parker, and Hay 1992). In addition, cumulative impact assessment (CIA) must not summarize and synthesize only individual impacts over time and space, but must also address interactions of individual impacts (Spaling and Smit 1993).

The CIA approach described in this technical report uses hydrologic indices to describe changes in long-term discharge patterns of rivers. These hydrologic indices may be linked with other information (e.g., spatial patterns in wetlands) to form cause-and-effect sequences between wetland hydrology, wetland spatial patterns, and wetlands functions, affecting habitat value (Croonquist and Brooks 1991). Developing and applying indices to

describe long-term changes in wetland hydrology relative to a single action will allow the effects of that action to be assessed against historical trends and patterns, thereby facilitating an understanding of the single impact within the context of past impacts on wetland hydrology.

Purpose

The CE, like the other agencies involved in wetlands preservation, is unable to consider cumulative impacts in its environmental assessments of wetlands impacts because of the unavailability of appropriate evaluation tools. Finding a simple means to describe, quantify, and isolate the historic H&H influences on a wetland would enable planners to deduce the hydraulic and hydrologic (H&H) processes responsible for current and perhaps future wetland conditions. Applications of relatively simple indices and summaries derived from flow and/or stage records, referred to as "hydrologic indices," to the Cache River wetlands are presented in this technical report as a case study of CIA. The concepts and methods presented in this report are most applicable to riparian wetlands. However, they can be easily modified for application to other wetland types. Where possible, suggestions are provided regarding how these modifications could be made.

A comparison document dealing with the climatic and agricultural impacts is in preparation.

2 Methods and Results

Hydrologic Indices

The hydrologic pattern for a specific riverine wetland is based on a complex interplay of numerous factors that determine timing and magnitude of discharges in rivers. Understanding hydrologic patterns is important because nearly all significant wetland processes can be wholly or partially described in hydrologic terms. Similarly, many alterations to wetlands (e.g., filling, draining, and stream regulation) can be characterized in terms of their alterations on the prevailing hydrologic regime (Schlosser 1991; Ehrenfeld and Schneider 1991). Thus, long-term changes in hydrologic patterns of wetlands may be used as a template upon which cumulative impacts can be identified, interpreted, and assessed. In addition, changes in spatial patterns of wetlands vegetation, described using tools such as the geographic information system (GIS), may be interpreted relative to changes in wetlands hydrology. Changes in hydrology and spatial patterns may be further linked to associated changes in other wetland values and functions to complete a CIA.

A variety of indices and summaries are available to describe hydrologic patterns in streams. They can be used to describe hydrologic patterns or to describe the hydrologic effects of wetland alteration on stream discharge patterns. The hydrologic indices presented here are based on long-term stream gauge data. Stream gauges record water elevations at specific locations, usually at specific intervals in river basins. These records of water elevation can usually be converted to estimates of mean daily flow. Stream gauges are deployed by a number of agencies, including the CE. The United States Geological Survey (USGS) maintains the most extensive network of stream gauges in terms of areas and times covered. Combined with runoff and drainage area information, synthesized gauge information for ungauged sites may be deduced from patterns in gauged streams within the basin.

Cache River Site Description

The Cache River basin, located in northeastern Arkansas 162 km upstream from the mouth of the White River (Figure 1), has been designated as a Ramsar[1] site. The gauging station of particular interest in the Cache River basin is located at Patterson, AR, and measures the primary inflow to the Cache River study area. The Patterson gauge has recorded the flow of the Cache River from a drainage basin of approximately 2,685 sq km for more than 60 years from January 1928 to the present. Because of the extensive coverage throughout time and the ready availability of complementary data, the Patterson gauge data were chosen to illustrate the hydrologic indices presented in this paper. Other gauges on the Cache River are at Egypt (draining an area of 1,815 sq km) and Cotton Plant (draining an area of 3,036 sq km), the location where primary outflow is measured. The Patterson and Cotton Plant gauges are approximately 49 river km apart. The location of the wetland of primary interest occupies about 350 sq km of the lower part of the drainage basin, with about 60 sq km of this area in bottomland hardwood forest. The wetlands upstream have undergone extensive channelization in the 1920s and 1930s to permit agricultural development in the area.

Questions concerning consistency of data collection methods or confounding effects from global climate change or decades-long drought cycles commonly arise during evaluation of long-term gauge data. Methods of data collection commonly change as technologies mature or change. In the case of the Cache River, the Patterson gauge was manually read at 0700 hours each morning until October 1949. Consequently, the pre-1949 gauge records are instantaneous measurements based on one daily observation. All subsequent readings are based on average daily stages from automatic stage recorders. Additionally, gauge readings collected prior to 1950 were characterized by flow values consistently above 40 cfs. Whether or not these readings represent inadequate calibration of the gauging sites or reflect actual flows in the river is uncertain. To address these data uncertainties, the results of some of the more innovative indices were compared with and without the suspect data included.

The effects of global climate change or long-term drought cycles are addressed by including in the analysis several other complementary gauging sites within the same basin or in nearby basins. Long-term results from these supplementary gauges were compared with results from the Cache River site to determine if hydrologic patterns in the Cache River were affected by alteration of internal hydrologic processes or external changes in climate, such as global warming or drought.

1 This site has been designated by the U.S. Fish and Wildlife Service to receive special study as one of a group of internationally recognized wetlands of critical ecological significance.

Simple indices and summary variables

These indices, defined in hydrology textbooks, describe measures of central tendency and dispersion. They provide a relatively low-resolution description or summary of complex hydrologic patterns. These indices are attractive primarily because of their intuitive simplicity, but they usually are not sensitive enough to reveal the sometimes subtle shifts in hydrologic patterns that often must be described when assessing cumulative impacts. Figure 2 shows the mean, maximum, and minimum annual flows for the Cache River at Patterson, AR, followed by corresponding values for the Buffalo River, the Eleven Point River, and the Little Red River (Figure 3). Annual summary statistics cannot describe time-dependent discharge changes critical to many wetland processes.

Mean annual discharge. Mean annual discharge (expressed as volume per unit time) is defined as the average of individual daily mean discharges (for 1 year) at a specific location on a river. This variable is commonly used to summarize the magnitude of discharge in a river; its applicability to assess impact is limited because the mean is heavily influenced by high discharge events that can mask effects of wetland alterations. Effects of impacts on wetlands that disrupt critical low discharge patterns are not usually well-described by this variable.

Median annual discharge. Median annual discharge is defined as the average daily discharge that is exceeded 50 percent of the time at a specific river location over a long period of record. Median annual discharge is less influenced by high discharge events and is, therefore, better for summarizing discharge patterns than is the mean annual discharge.

Mean/median monthly discharges. Mean/median monthly discharges are the mean/median of daily discharges by month. Mean or median monthly discharges can sometimes depict the effects of wetland alterations on system hydrology during the dry season. However, describing long-term effects of a wetland alteration in terms of changes in monthly median flows often is inadequate because such analyses may not accurately detect or adequately describe changes in patterns between months, particularly if lower flows are assessed. Figure 4 presents decade-by-decade median monthly flows for the Cache River. Note that pattern changes in median flows between decades are difficult to detect. Succeeding figures show each month as changes in median, mean, and maximum occurring decade-by-decade.

Ranges of discharge. Ranges of discharge are used to describe the extreme values that may be recorded by the stream gauge. Ranges are typically defined on a monthly, seasonal, or annual basis. Figure 5 shows trends for each decade by month.

Discharge-duration curves. Discharge-duration curves give the duration of occurrence of particular ranges of discharges in the river. Discharge-duration curves are often a useful means of describing hydrologic patterns

or characterizing the effects of wetland alteration on hydrologic patterns. The 75- or 90-percent exceedance discharge range conveniently describes low discharges in a system while not overemphasizing single extreme low values. The 10- or 25-percent exceedance discharge can be used to describe high discharges without being overly influenced by a single extremely high measurement. The effect of a particular wetland modification on wetland hydrology can often be initially described using discharge-duration curves. However, changes in hydrologic patterns using discharge-duration curves are difficult to discern because so many curves are required (60 curves - 12 months times 5 decades) to describe long-term trends. Flow-frequency trends of the Cache River at Patterson for the decades of interest are summarized in Figure 6, while distribution of flows of the Cache River at Patterson is compared with three other streams in close geographic proximity and with median flows of about the same magnitude in Figure 7. Flow distributions of the Buffalo River, the Eleven Point River, and the Little Red River are found at Figures 8, 9, and 10.

Complex indices and summary methods

The indices that follow are formulated to describe temporal patterns in a series of hydrologic data such as are commonly available from long-term gauge records. They may be more difficult to employ than the simple indices, but they can depict subtle changes in hydrologic trends with potential biological significance. Because many wetland biota require different hydrologic conditions at each of their life stages, understanding long-term hydrologic patterns as well as focusing on specific months is critical. Consequently, it is important to view the effects of a wetland alteration in terms of its overall effect on annual hydrologic patterns. Assessing the effect of a wetland alteration using annual or monthly summaries restricted to 1 or a few years or months may result in misleading conclusions.

Advanced hydrologic methods (e.g., spectrum analysis using Fast Fourier Transformation) are also available, but are not generally employed in cumulative impact analysis because of resource or training limitations and difficulty of interpretation. The following methods have been adapted or developed because they are mathematically simple and easy to apply, and the results are relatively easy to interpret. More importantly, they have a resolution and scale selected to facilitate relating biological processes to hydrologic patterns. While the focus of this paper is riverine wetlands, harmonic analysis and time-scale analysis can also be used to describe or assess changes in water surface elevation patterns in lacustrine (lake) wetlands.

The results obtained for the Cache River are compared with other sites in the region because of changes in the procedures used to collect stage data that could affect the results of the analysis. The effect of changes in data recording or confounding effects of global climate change would be inferred if similar trends are observed across multiple basins.

Harmonic analysis. Harmonic analysis evaluates the fit of a time series of data to a harmonic (usually cosine or sine) function. Harmonic analysis typically generates four coefficients—mean, period, phase, and amplitude—that can be used to describe a process that approximates a harmonic function. Each of the coefficients provides reasonably well-defined information about complex hydrologic time series (Trost 1991). These coefficients can be used singly or in various combinations to describe hydrologic patterns. For example, the mean provides information about the central tendency of the pattern; the phase (usually expressed as an angle in radians) provides information about the seasonality of the discharge pattern, and the amplitude provides information on the range of hydrologic conditions to be expected over a single period (usually 1 year).

The underlying pattern in monthly discharges at different streams can be explored and summarized using harmonic analysis of log-transformed mean monthly discharge data when the underlying annual discharge pattern of the river system approximates a cosine function (with period = 1 year). Log-transformed data are more meaningful surrogates of habitat quality than untransformed data (i.e., gauged discharge data) because both water depth and water velocity in streams can usually be expressed as simple power functions of discharge at a given cross section. Thus, stage changes in wetlands over long time periods can be inferred by harmonic analysis, even when stage information (water surface elevation) may not be available directly.

Harmonic analyses of the Cache River gauge data were based on stream gauging records as displayed in "National Water Conditions" published by the U.S. Geological Survey. Patterns in mean (minimum, maximum) monthly discharges at 10-year (and 5-year) intervals were evaluated by fitting them to a cosine function employing nonlinear regression (SAS Institute, Inc. 1988) using

$$LMEANQ_{(i)} = AMP \times \cos[(MONTH + PHS) \times PER \times pi]$$

where

LMEANQ = log-transformed mean (minimum, maximum) monthly discharge (standardized to a mean of 0.0)

AMP = amplitude

MONTH = coded such that $0.0 < MONTH < 1.0$

PHS = phase

PER = period

The above procedure was applied to weekly mean discharges as well.

For each gauge location, harmonic analysis allows one to infer the probable dominant hydrologic factors (e.g., groundwater, winter rain, and snowmelt) that determine hydrologic patterns by evaluating the values of

the coefficients produced by the nonlinear regression. For example, a "seasonality index," the absolute value of the ratio of amplitude of mean monthly discharges to mean of monthly discharges (assuming that the discharges follow a sinusoidal pattern), can be used to estimate the degree of seasonality in mean monthly discharges. This index has been defined here such that low values of this ratio indicate that discharges occur randomly (or in nonannual periods), whereas high values indicate that discharges fall within distinct seasonal patterns. Western streams receiving substantial amounts of snowmelt (e.g., Changnon, McKee, and Doesken 1991) typically exhibit high seasonality indices (Nestler 1993).

Seasonality indices based on monthly mean flows (also minimum mean monthly flows, maximum mean monthly flows, and median mean monthly flows) for periods of record examined for the Cache River at Patterson and the other rivers are compared in Figure 11. This analysis reveals that (a) the Buffalo and the Eleven Point rivers exhibit little change in seasonality pattern of mean and maximum over their respective periods of record; (b) the Little Red River, under complete regulation by Greers Ferry Dam since March of 1962, appears to take an abrupt plunge in the seasonality index of the minimum mean in the decade beginning in 1961; (c) the Cache River at Patterson exhibits an erratic trend in the seasonality index of the minimum; (d) the minima exhibit higher levels of seasonality for each of the rivers examined except for the Eleven Point River, although this high value is most pronounced in the Little Red River prior to impoundment in the 1960s; and (e) the Eleven Point River showed least differences among its means, minima, and maxima. From the analysis, these authors conclude that hydrological processes in the Cache River basin that operate on a monthly time scale have been altered to the extent that the seasonal discharge pattern in the Cache River wetlands has been affected.

After the decade of the 1950s, the disruption in the seasonal pattern of monthly minimum mean discharges is characterized by a reduction in the lowest monthly mean discharges and a loss in the seasonal pattern of low discharges evidenced by minimum means not following the general pattern of the means or the maximum means (see Table 1). Each decade shows increased winter and spring discharge probably related to the effects of increased winter and spring rainfall (Figure 4). The harmonic analysis for the Cache River maxima, mean, and minima of monthly mean discharges (Figure 12) indicates that a disruption in the pattern of the lowest of the mean discharges occurred in the decade of the 1950s (the individual points do not conform as closely to the curve of best fit).

A comparison of the harmonic patterns observed for the Cache River with the other sites indicated that the patterns in the Cache River were unique and could not be attributed to regional drought patterns or global warming. The Buffalo River near St. Joe, AR (Figure 13), had monthly mean discharges with minima, means, and maxima appearing to be in phase for all decades examined (1941-90). Seemingly uncharacteristic late year lows occurred in the decades of 1951-60 and 1961-70.

Table 1
Pearson Correlation Coefficient Values for Flow Parameters of Selected Area Streams

Decade	Pearson Correlation Coefficients Log-Transformed Discharge, cfs					
	Weekly			Monthly		
	Mean to Minimum	Minimum to Maximum	Mean to Maximum	Mean to Minimum	Minimum to Maximum	Mean to Maximum
Buffalo River near St. Joe, AR						
1941-50	0.84*	0.92*	0.65*	0.93*	0.92*	0.80*
1951-60	0.88*	0.96*	0.77*	0.92*	0.96*	0.86*
1961-70	0.74*	0.95*	0.57*	0.77*	0.97*	0.69*
1971-80	0.79*	0.95*	0.66*	0.84*	0.99*	0.80*
1981-90	0.68*	0.96*	0.54*	0.69*	0.92*	0.46
Eleven Point River near Bardley, MO						
1941-50	0.62*	0.92*	0.48*	0.66	0.93*	0.65
1951-60	0.76*	0.91*	0.56*	0.83*	0.93*	0.68*
1961-70	0.60*	0.88*	0.31	0.74*	0.88*	0.51
1971-80	0.61*	0.93*	0.52*	0.68*	0.94*	0.59
1981-90	0.28	0.91*	0.10	0.24	0.93*	-0.03
Little Red River near Heber Springs, AR						
1921-30	0.84*	0.99*	0.76*	0.94*	0.99*	0.91*
1931-40	0.87*	0.98*	0.81*	0.90*	0.98*	0.87*
1941-50	0.72*	0.93*	0.54*	0.66	0.92*	0.56
1951-60	0.71*	0.96*	0.56*	0.77*	0.95*	0.50
1961-70	0.71*	0.95*	0.60*	0.83*	0.97*	0.76*
1971-80	0.20	0.89*	0.05	0.01	0.90*	0.03
1981-90	0.48*	0.97*	0.25	0.27	0.92*	-0.13
Cache River at Patterson, AR						
1921-40	0.77*	0.96*	0.62*	0.86*	0.93*	0.64
1941-50	0.78*	0.92*	0.66*	0.78*	0.91*	0.75*
1951-60	0.67*	0.96*	0.55	0.76*	0.96*	0.63
1961-70	0.36	0.93*	0.25	0.31	0.93*	0.25
1971-80	0.39	0.86*	0.11	0.41	0.89*	0.17
1981-90	0.00	0.87*	-0.34	0.09	0.89*	-0.22

Note: * means P = <0.02.

The Eleven Point River near Bardley, MO (Figure 14), exhibits a minimum mean discharge of small amplitude, not varying with the mean and maximum except for the decades of 1951-60 and 1961-70, in which the minimum seem to be in phase with the mean and maximum. The minimum again appears to be out of phase in the decades of 1971-80 and 1981-90. In all decades, however, the fluctuation of the minimum throughout all months is limited.

In the case of the Little Red River (Figure 15), only four decades (1931-1990) should be considered since the record of the decade of 1921-30 did

not begin until September 1927. Moreover, the station was discontinued as a continuous-record station and converted to a crest-stage partial-record station in September 1980. Most importantly, the flow has been completely regulated since March 1962 by Greers Ferry Dam, with some regulation from October 1960 to February 1962 by the construction of Greers Ferry Dam. River regulation has had a profound effect on harmonic patterns of flow in the Little Red River. In the decade prior to regulation, the minimum monthly mean reached an extreme low (<10 cfs) near the end of the year, but the decade of the regulation showed a very constant minimum for all months of the year (~100 cfs). In the decade of 1971-80, the minimum exceeded 100 cfs for all months, varying in a markedly different way from the mean and the maximum.

To explore further which part of the flow range was affected, correlation analysis among minimum, maximum, and mean monthly discharges was performed for each stream. High correlations between mean, minimum, and maximum discharges for a single site imply that extremes in wet and dry periods tend to fall within the same general hydrologic pattern as the mean monthly discharge summary, whereas low correlations suggest that extended (monthly) extreme discharge conditions occur randomly or in a pattern different from mean monthly discharges. Consequently, trends in correlation coefficients among decades can be used to deduce in which part of the hydrograph changes in flow patterns have occurred. Correlation statistics by decade and among mean, minimum, and maximum monthly (weekly) means for the gauges on the Buffalo River near St. Joe, AR, the Eleven Point River near Bardley, MO, the Little Red River near Heber Springs, AR, as well as on the Cache River at Patterson, AR, are given in Table 1.

It is reasonable to expect the changes in hydrology identified by harmonic analysis to affect aquatic and/or wetland biota requiring certain seasonal hydrologic patterns for successful completion of their propagation and/or early life stages (Bayley 1991). Harmonic analysis was useful in detecting changes in hydrologic patterns in the Cache River, particularly in the behavior of minimum mean flows. However, its usefulness was limited by not providing enough insight into the factors responsible for the decade-to-decade changes. From the standpoint of cumulative impact analysis, the harmonic analysis did not generate sufficient information to correlate with land-use changes or other long-term changes in the basin that could, in turn, be used to understand why the hydrologic patterns may have changed. To supplement the harmonic analysis, comparative time-scale analysis was performed on the Cache River discharge data.

Comparative time-scale analysis. Many time series exhibit pronounced time-scale dependent behavior. For example, tide gauge information can be decomposed into a number of different harmonic patterns, each based on a different period and each representing the effects of separate influences on tide dynamics (i.e., diel, lunar, solar, localized, and interactive influences). Similarly, stream gauge readings can also exhibit pronounced time-scale dependent behavior because many of the separate

hydrologic factors that blend together to generate a characteristic pattern at a gauge each have an associated unique time scale. For example, snowmelt can increase summer flows for a period of a month to several months (Changnon, McKee, and Doesken 1991). Groundwater recharge can provide a relatively constant base flow. Seasonal rainfall patterns associated with the passage of fronts will result in periods of increased flows lasting several months during a seasonal wet period. Conversely, synoptic rainfall events associated with localized summer rain storms occur more or less randomly and will influence gauge records for a period of up to 1 week, depending upon the duration and intensity of precipitation, runoff characteristics of the basin, and the area of the basin covered by the storm. Changes in the importance of different hydrologic factors in a long period of record can be assessed by evaluating changes in time-scale behavior at intervals along the record. A variety of methods, most based on application of arithmetic moving average methods (e.g., ARMA—auto-regression moving average), are available to assess time-scale behavior. However, these methods have limited usefulness for CIA because they require advanced training, the results are often difficult to interpret, and their primary utility is to synthesize data instead of providing direct insight into changes in hydrologic processes.

Studies in fractal geometry (Peitgen and Richter 1986; Turcotte 1992) suggest that seemingly complex physical features, such as stream networks, mountain ranges, and clouds, and complex physical processes, such as turbulence and stream flow patterns, exhibit the same pattern repeatedly; but over increasingly smaller distances or time scales, they exhibit "fractal properties." For example, the margins of a cloud, when viewed from a distance, exhibit gentle billows. However, as the observer moves closer to the cloud, the large billows are seen to be comprised of smaller billows comprised of still smaller billows until a limiting scale is approached.

An important fractal property, the fractal dimension, is commonly obtained using a "method of rulers." In this approach, progressively larger rulers are used to measure the perimeter of physical feature. A straight-line relationship between the common logarithm of both ruler length and perimeter is indicative of strong fractal properties (the slope of this line is termed the "fractal dimension"). This relationship implies that a single underlying pattern is being repeated, but at different scales, within the feature.

Hydrologic time series are also known to exhibit fractal properties. For the Cache River application, these properties were described using discharge averages ("time dimension") based on different durations instead of rulers of different lengths ("distance dimension"). However, the concept of evaluating information lost as a function of the resolution of measure is similar. Mean monthly flows were calculated for each month for the period of record. Synthesized daily flows were obtained by linear interpolation between adjacent months. The error between the synthesized daily flows based on monthly means and the measured daily flows represents primarily the contribution

of hydrologic processes that occur at a duration greater than 1 day and less than 1 month. Examination of these errors between different basins or between different time periods at one site can provide insight into the dynamics of hydrologic processes that operate for a duration of less than 1 month.

The concept can be expanded to generate synthesized daily flows based on many different time durations. The error between each of the synthesized daily flows and the measured daily flows represents the relationship between the different hydrologic processes that blend together to generate a hydrograph. Long-term trends in these errors indicate changes in the relative contribution of different hydrologic processes to the site hydrograph and can provide valuable information for CIA of wetlands by providing a partial hydrologic explanation for the results obtained using the simple indices and the harmonic analysis.

Root mean square error (RMSE) calculated as

$$\mathrm{RMSE} = \left[\frac{\sum (S_{i+1} - S_i)^2}{\mathrm{NOBS}} \right]^{1/2}$$

where

S = synthesized daily discharge based on successive time scales

NOBS = number of observations

RMSE is used to measure errors between recorded and synthesized daily flows based on different durations. An increase in RMSE beginning in the decade prior to 1951 is apparent in the decade-by-decade comparisons in which each decade begins in a year ending in "1."

The RMSE between pairs of time scales generally increases each decade for the period of record. The shorter time intervals (1 to 3 days, 1 to 7 days) are not as affected over time as the longer intervals. When the decades are offset by 5 years (i.e., the last year of each decade ends in "5"), the curves change slightly; but the overall increase in decade-by-decade RMSE for the longer time intervals remains. The same consistent pattern remains when the analysis is performed at 5-year instead of decade intervals. Figure 16 presents an expansion of the time-scale analysis in which error trends are generated based on daily , 3-, 7-, 15-, 29-, and 59-day average discharges. In each case, the time series was begun on 1 January of each year, reset at the end of each year, and restricted to monthly discharges less than 200 cfs. The analysis was restricted to lower flows based on findings from the harmonic analysis and discharge-duration curves showing changes between decades being primarily during low flows. Average daily discharge values between time increments for each time span were obtained by linear interpolation (e.g., average daily discharges at Days 2-7 are estimated

from Week 1 discharge of 100 cfs and a Week 2 discharge of 170 cfs as 110, 120, 130, 140, 150, and 160 cfs). Comparisons are made between discharges at 5 intervals: (a) daily to 3 days, (b) 1 to 7 days, (c) 1 to 15 days, (d) 1 to 29 days, and (e) 1 to 59 days to characterize changes in hydrologic patterns in the Cache River at low discharges.

The time-scale analysis on the Cache River at Patterson was repeated using discharges exceeding 40 cfs because the methods used to collect stage-discharge information prior to October 1949 may have used default values of 40 cfs for low flows. Regression analysis of the respective root mean squares of data including and not including flows 40 cfs or less revealed that the two sets of data were significantly correlated ($p < 0.01$) and that the inclusion or rejection of the suspect data did not change the conclusions obtained from the analysis (Figure 16), i.e., that flow was more uniform before 1950 than afterward.

Other gauges in the area were examined in like fashion to determine if they were similar to the Cache River. These were Buffalo River near St. Joe, AR, Eleven-Point River near Bardley, MO, and Little Red River near Heber Springs, AR. Characteristics of various streams at/near the specified gauge locations are given at Table 2. The flow limits of the Buffalo River and Eleven Point River were set to the same upper and lower bounds—200 and 40 cfs, respectively—as were applied to the Cache River at Patterson. When these results failed to show "definition," the analyses were rerun using all flows in the RMSE calculations. The RMSE values of each of the streams compared with the Cache River at Patterson (all flows considered) are graphed in Figure 17.

Table 2
Characteristics of Streams/Gauges Considered

Gauge	Drainage Area, sq mi	River Mile	Daily Flow, cfs Maximum	Mean	Minimum
Cache River					
at Egypt	701	143	8,940	827	0
at Patterson	1,037	77.2	12,100	1,257	0
at Cotton Plant	1,172		10,900	1,351	25
Buffalo River near St. Joe	829	58.3	158,000	1,026	6.6
Eleven Point near Bardley (1921-1992)	793	53.7	26,800	771	152
Little Red River near Searcy	1,648	31.7	35,300	2,459	0
Little Red River near Heber Springs (1927-1980)	1,153	78.8	117,000	1,764	0

In the analysis of the Buffalo River, all of the respective intervals (RMSE1-5) seem uncharacteristically low in the decade of 1931-40 when

compared with the other decades. The range of RMSE is from ~100 cfs in the 1961-70 decade to over 3,000 cfs in the decade of 1941-50.

Throughout the decades considered in the analysis of the Eleven Point River, all RMSE intervals had roughly equivalent trends. The highest values for each RMSE interval was found in the 1941-50 decade, with the lowest in 1931-40.

The time-scale analysis of the Little Red River flows shown in Figure 17 reveals the decade in which the river was impounded, with resulting stabilization of flows. Each time period for which the root-mean-square error was calculated (3-day periods to 2-month periods) reflected marked damping of flow fluctuation. All flows were considered in the analysis in order to detect and to demonstrate the abrupt change wrought by regulation, whereas time-scale analysis of the Cache River at Patterson (Figure 16) was restricted to flows less than 200 cfs in an attempt to discern suspected changes to base flow conditions. When all flows are considered for the Cache River at Patterson as for the other three streams (Figure 17), the RMSE intervals from decade to decade are essentially flat, with RMSE1 less than 200 cfs, and RMSE5 greater than 1,200 cfs. This pattern offers sharp contrast to the Cache River at Patterson analyzed with only flows less than 200 cfs.

3 Conclusions and Summary

The hydrological analyses presented herein, particularly the harmonic analysis and time-scale analysis, all indicate that patterns in low flows (less than 200 cfs) at the Patterson gauge of the Cache River have changed gradually and consistently from the decade of the 1950s to the present. This analysis suggests that low discharges during the decades prior to 1950 were dominated by hydrologic processes (possibly groundwater recharge, water stored within the watershed by forested land, or water stored within the wetland; but since appropriate records are unavailable, this can only be inferred on the basis of literature findings from other wetlands) that provided a generally stable base discharge.[1] Consequently, during periods of prolonged drought, the low discharge hydrograph was dominated by a generally persistent and stable hydrologic process prior to 1950. After 1950, the error between daily flows based on different time scales increased. The timing and duration of low discharges from the decade of the 1950s to the present are probably increasingly dominated by some hydrologic process operating over a short time period and not by groundwater recharge or recharge from stored water within the basin or wetland. Armstrong and Garwood (1991) describe the effects of drainage on runoff characteristics. Similar links between groundwater and wetland hydrology have been observed at other sites (Lloyd et al. 1993; Armstrong and Garwood 1991; Gehrels and Mulamoottil 1990; Suso and Llamas 1993; Shedlock et al. 1993; Bernáldez, Rey Benayas, and Martínez 1993), and the interplay between groundwater and streamflow is well known (Trémolières et al. 1993; Bickerton et al. 1993). Clear-cutting of forest or conversion to grassland also alters flow frequencies (Burt and Swank 1992; Anderson et al. 1993; Gustard and Wesselink 1993; Calder 1993).

The effect of changes in the low flow hydrograph on spatial patterns and wetlands fauna are presently the topic of ongoing work and will be documented in another report. Preliminary analyses suggest that groundwater pumping, as indicated by acreage planted of crops requiring irrigation, has increased at a rate that corresponds to the loss of pattern indicated by the harmonic and time-scale analysis. Relatively short duration records

[1] Preliminary analysis of other data indicates there is sufficient head to cause the wetland to be a groundwater discharge area during much of the year (Kleiss 1993).

of groundwater levels indicate a gradual and consistent reduction in groundwater levels (Tighe, in preparation). This same relationship between alteration of drainage characteristics in a basin and wetland hydrology has been observed at other sites (Roulet 1990). However, it may be impossible to determine the effects of altered hydrologic patterns on the fauna and flora of the unimpacted Cache River wetlands because ongoing studies can only document present wetland conditions.

The CIA studies conducted on the Cache River have demonstrated that changes in the basin and wetlands have probably contributed to specific changes in hydrologic patterns in the wetlands. The computational tools identified in this report may be useful for characterizing hydrologic processes producing impacts likely to affect wetland vegetation, wildlife, and aquatic biota in the Cache River System. However, these changes may be unique to the Cache River and should not be extrapolated to other wetlands. Each wetland should be analyzed individually.

This technical report presents a suite of hydrologic indices and summary variables with potential for describing and exploring the effects of hydrologic perturbations that can contribute to impacts on wetlands. These indices range from intuitively simple but generally insensitive indices such as means, medians, ranges, and discharge-duration curves to indices that are sensitive to subtle changes in hydrologic patterns. One such sensitive index, provided in harmonic analysis, is relatively simple to perform and useful to explore changes in the pattern of discharges or stages in wetlands. The time-scale analysis can be employed to provide a relatively high resolution quantification of changes in hydrology that can be related to long-term changes in land or water use patterns linked to the changes in wetlands.

The hydrologic analyses presented here can be used as the basis of CIA. From a cumulative impact assessment standpoint, any alteration of the wetland that causes the low flow hydrograph of the Cache River to be more "flashy" by eliminating base flow or increasing runoff rates will contribute to the further degradation of the historical hydrologic pattern of the wetland and should either be avoided, mitigated, or minimized. Conversely, any activity that shifts these patterns towards 1930-1940 patterns should be encouraged. If cause-and-effect linkages between land use patterns, hydrologic time scales, and biotic response can be determined, then determination of cumulative impacts resulting from hydrologic changes on wetlands is possible.

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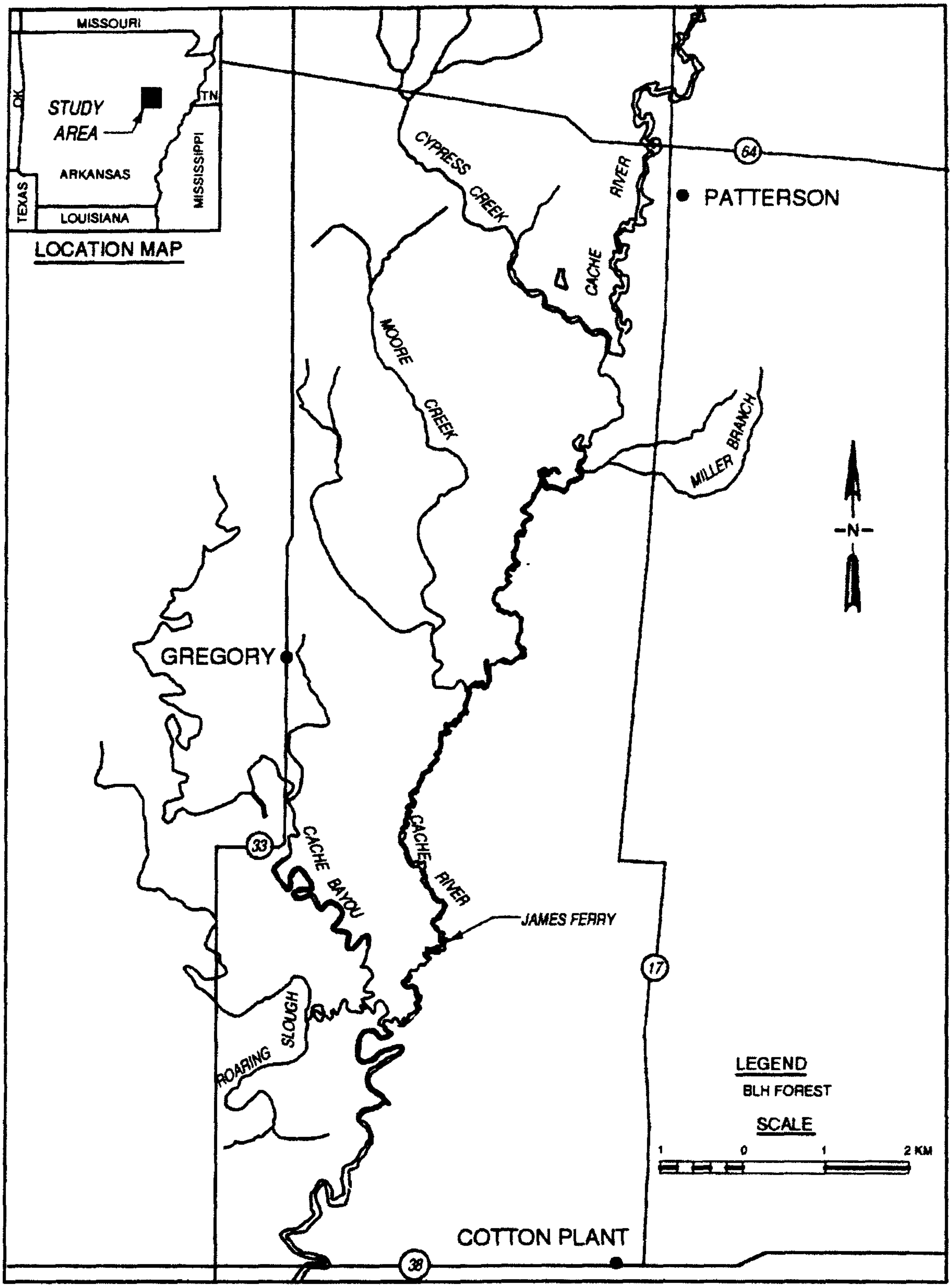


Figure 1. Cache River Study area

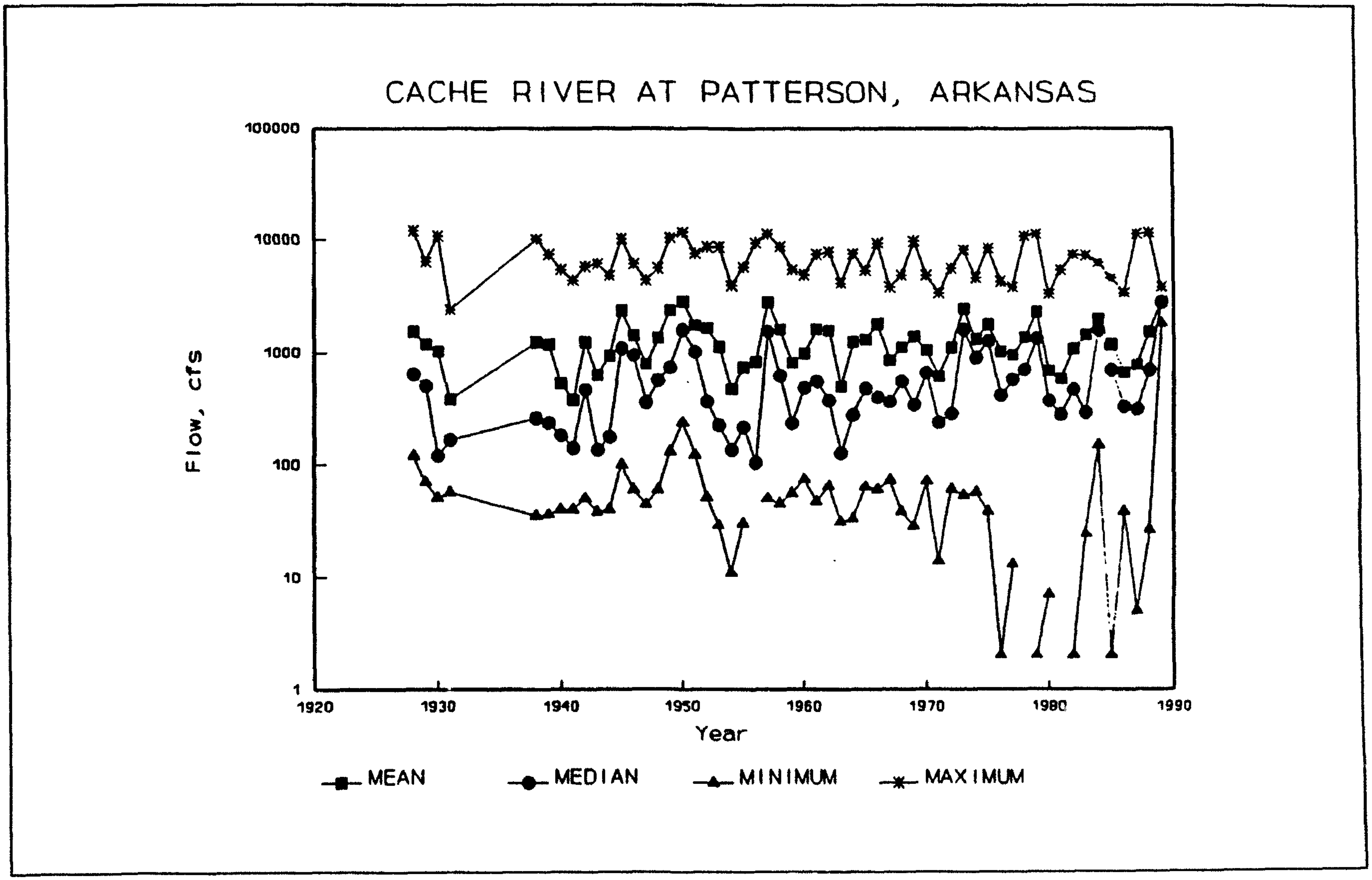


Figure 2. Simple annual statistics describing historic flow (cfs) of the Cache River at Patterson, AR

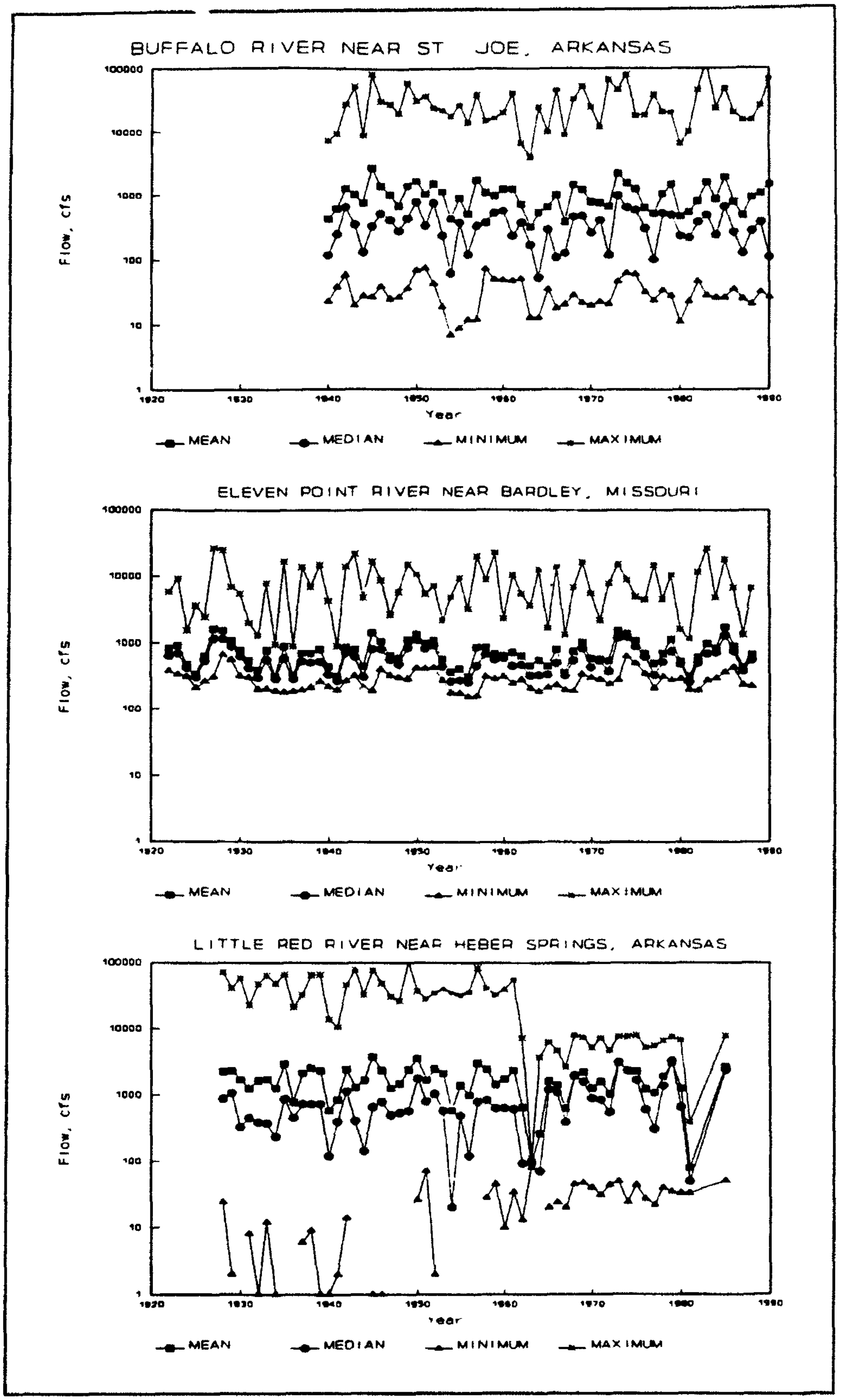


Figure 3. Simple annual statistics of stream flows of the Buffalo River, the Eleven Point River, and the Little Red River

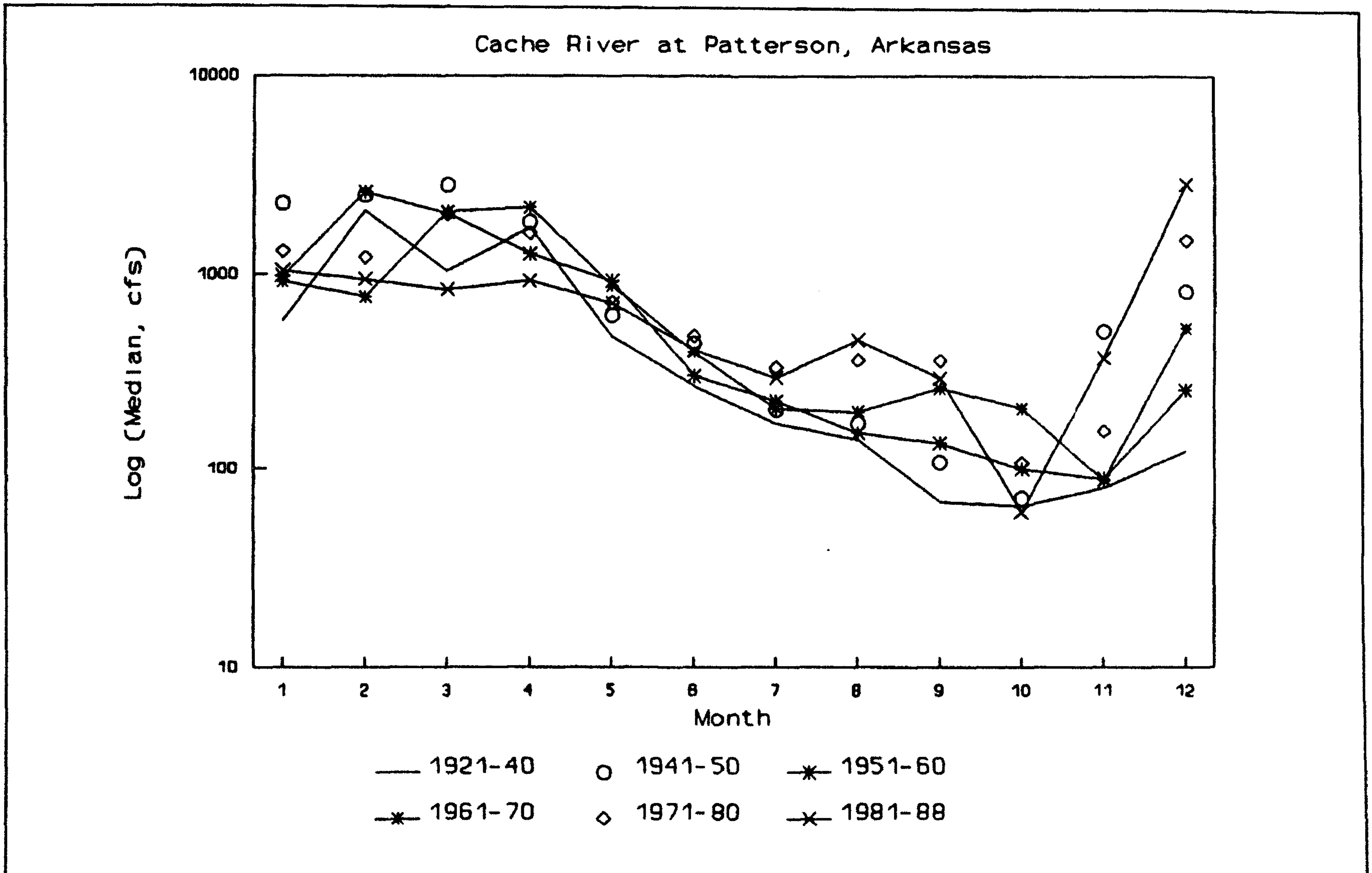


Figure 4. Decade-by-decade comparison of flow statistics compared by decade by month for the Cache River at Patterson (Sheet 1 of 4)

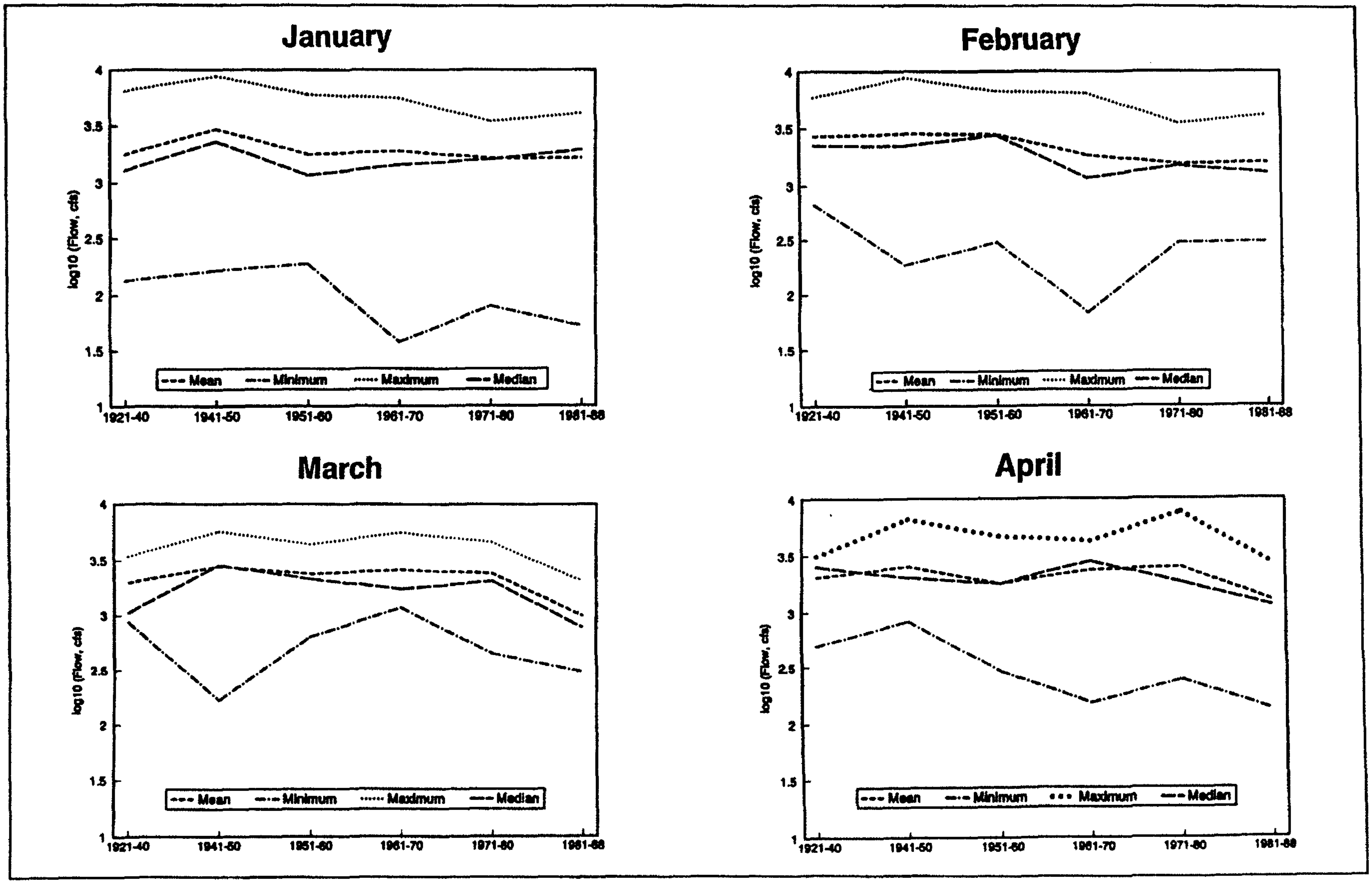
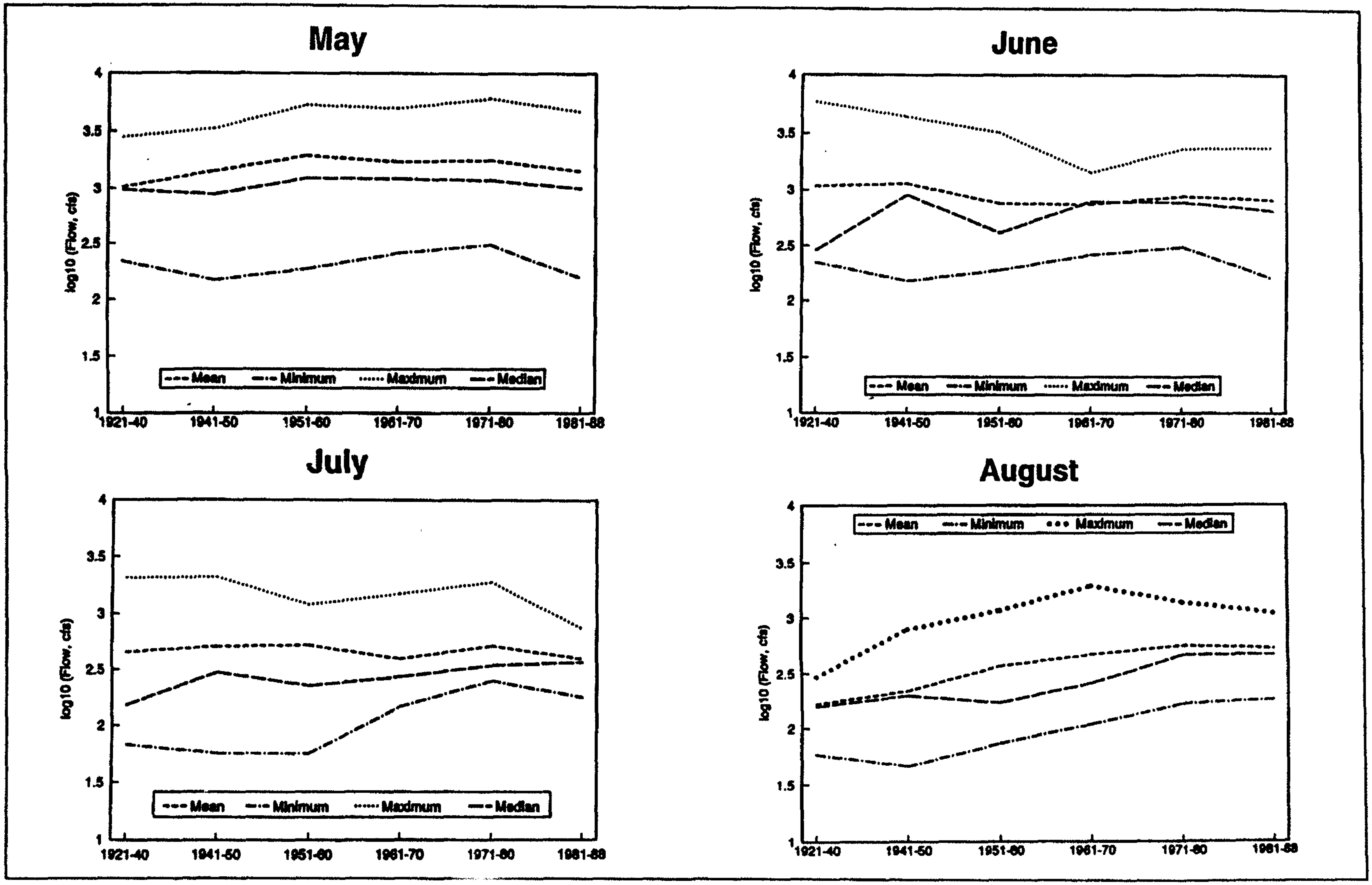


Figure 4. (Sheet 2 of 4)



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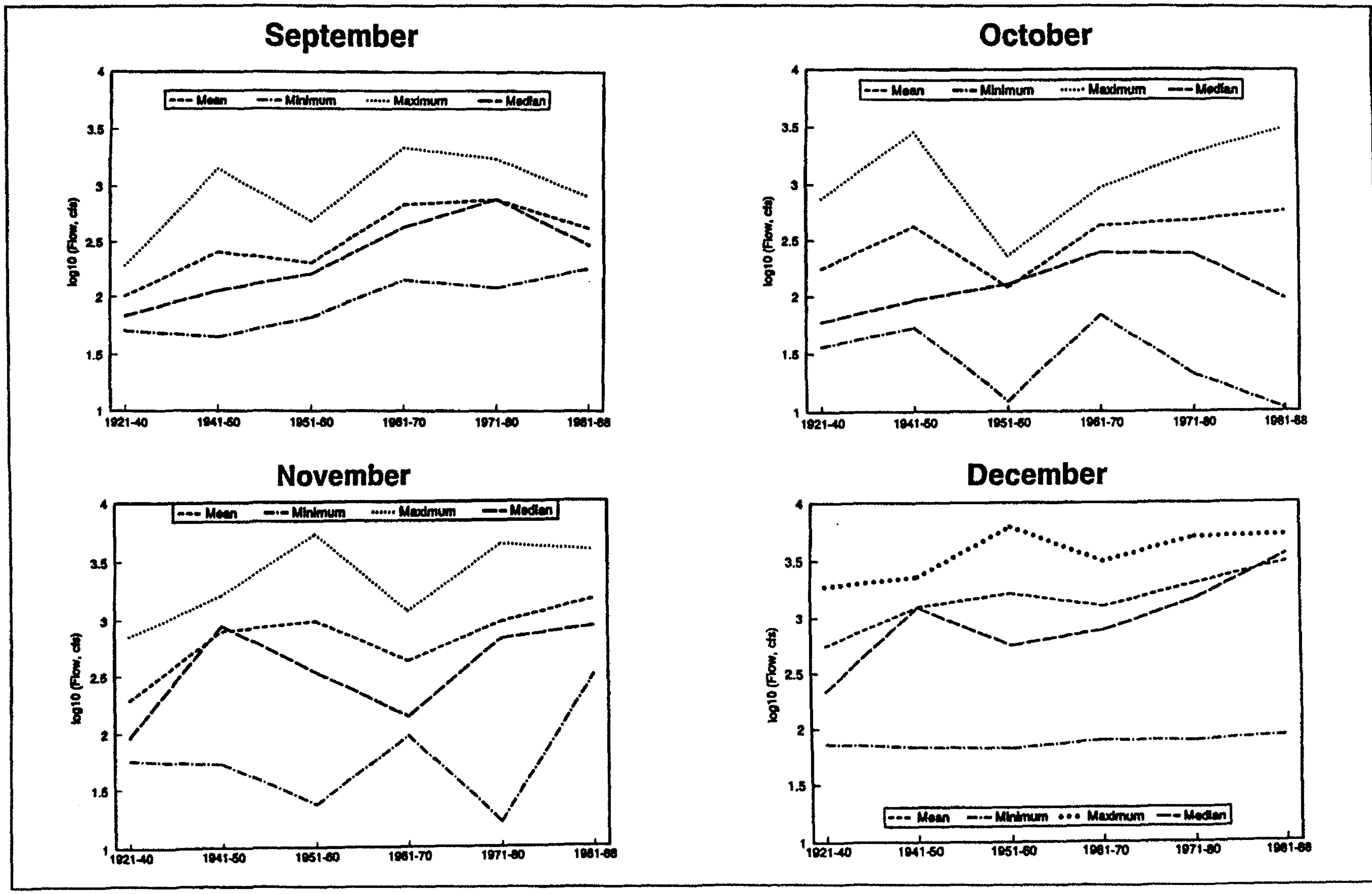

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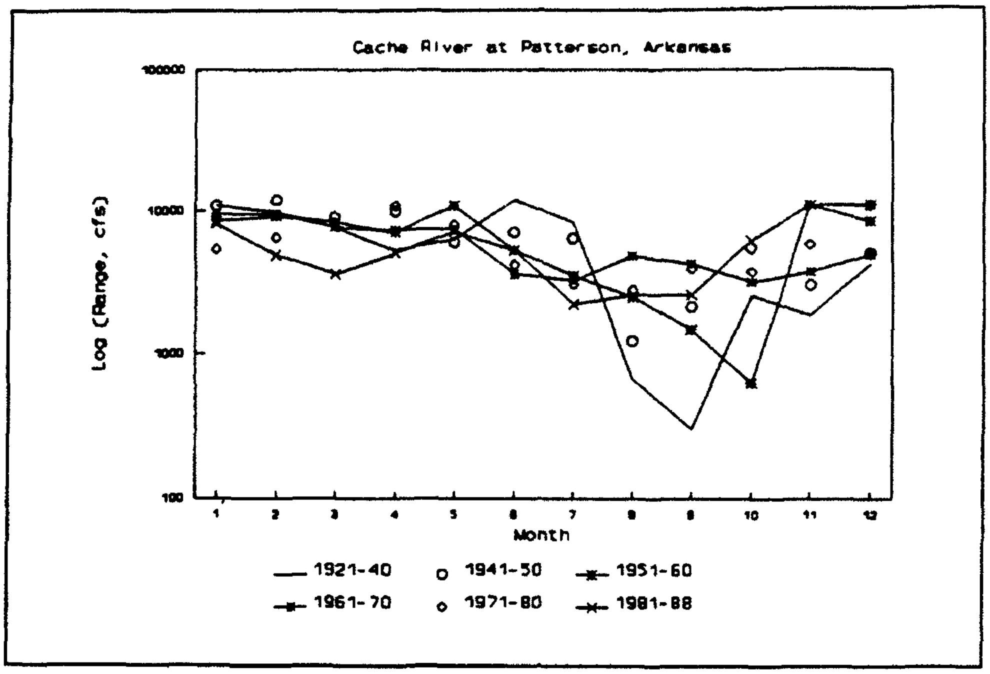


Figure 5. Decade-by-decade comparison of monthly ranges of flows

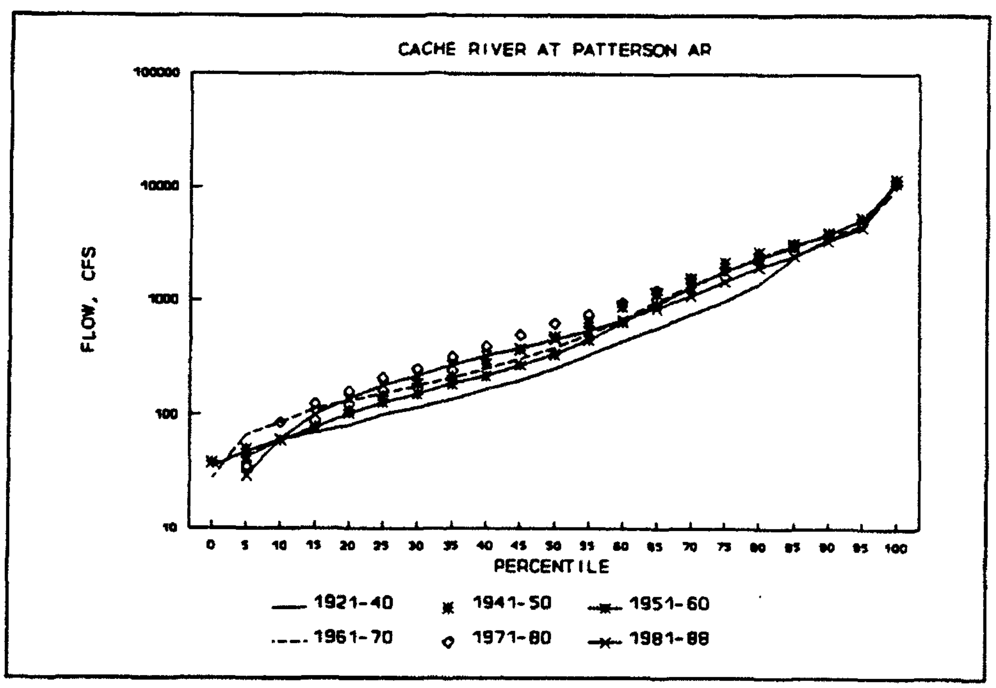


Figure 6. Decade-by-decade comparison of flow distribution

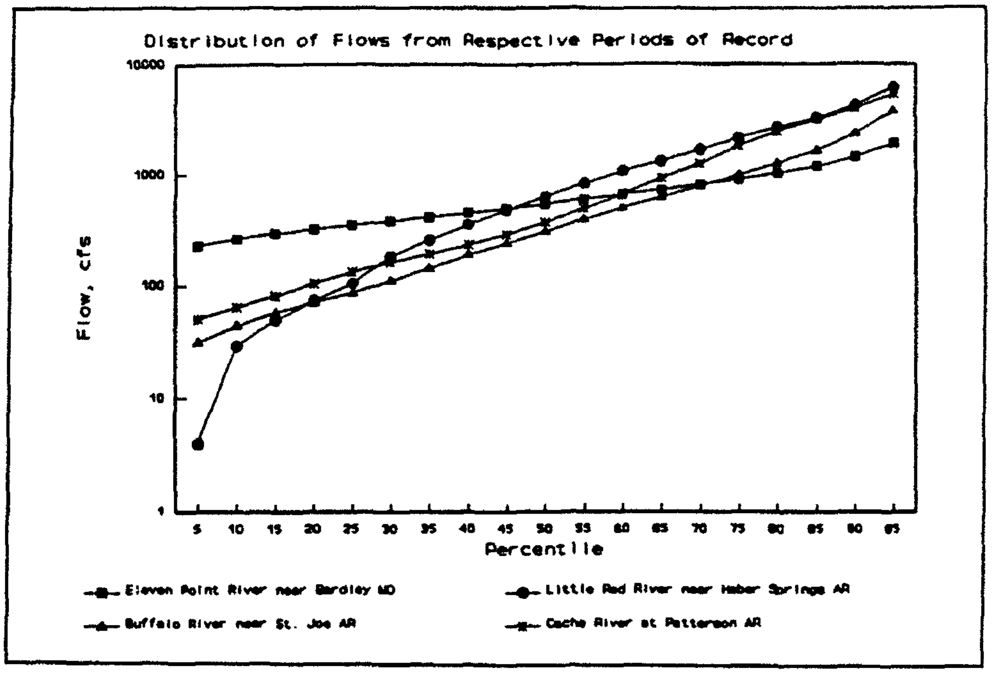


Figure 7. Distribution of flows of comparable streams in the White River basin, Arkansas/Misssouri

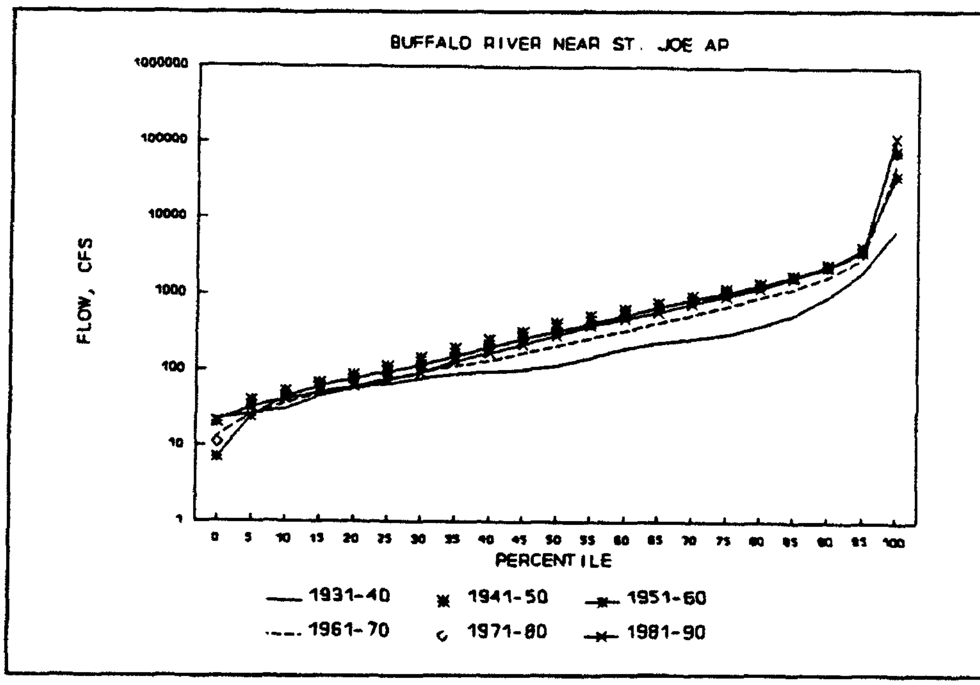


Figure 8. Flow distribution for the Buffalo River near St. Joe, AR

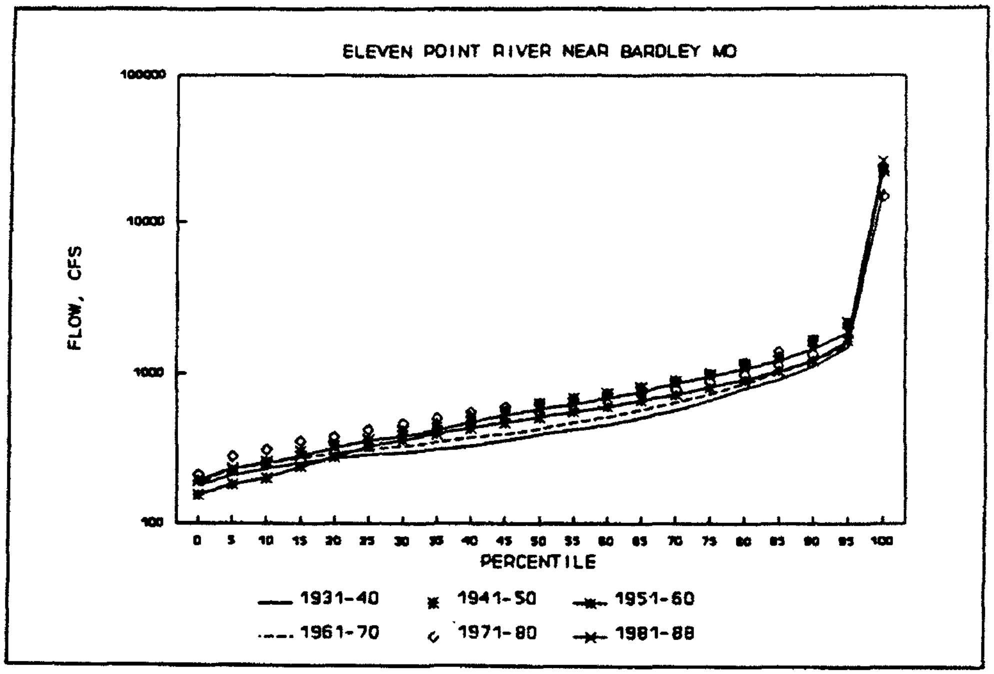


Figure 9. Flow distribution for the Eleven Point River near Bardley, MO

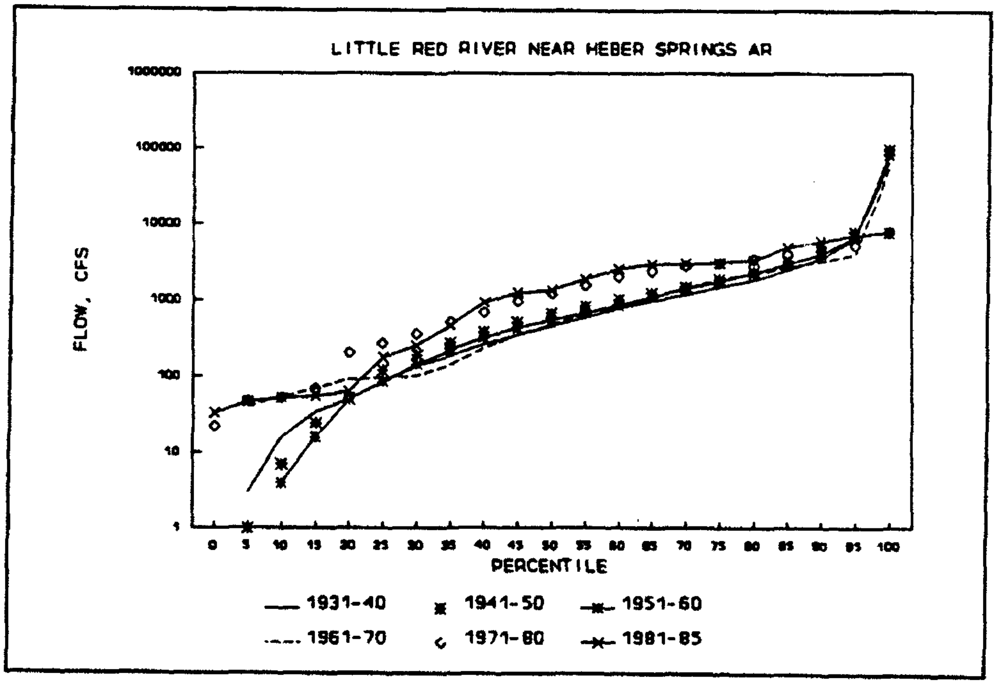


Figure 10. Flow distribution for the Little Red River near Heber Springs, AR

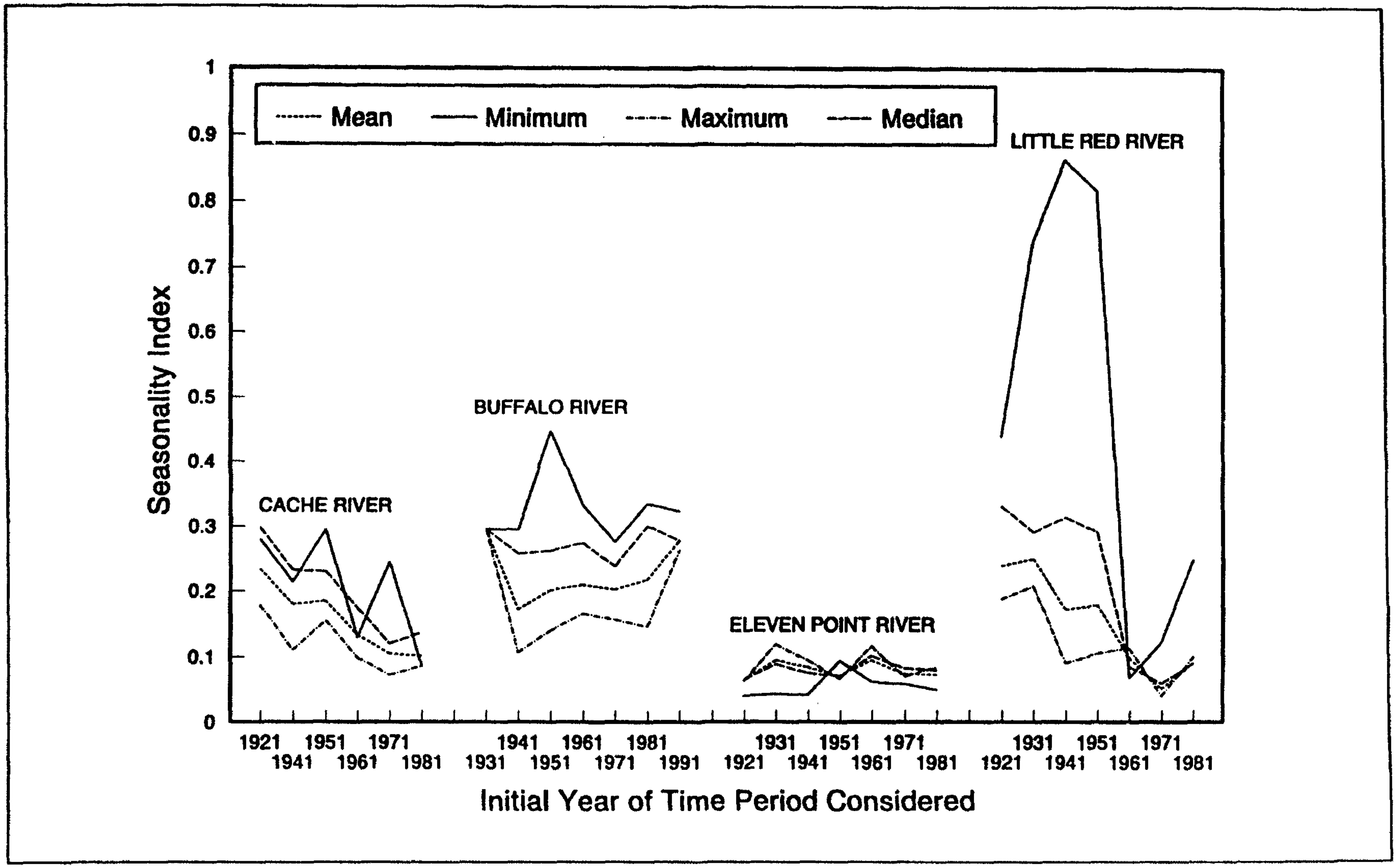


Figure 11. Seasonality indices of means, minima, maxima, and medians compared for four gauges in the White River Basin, Arkansas/Missouri

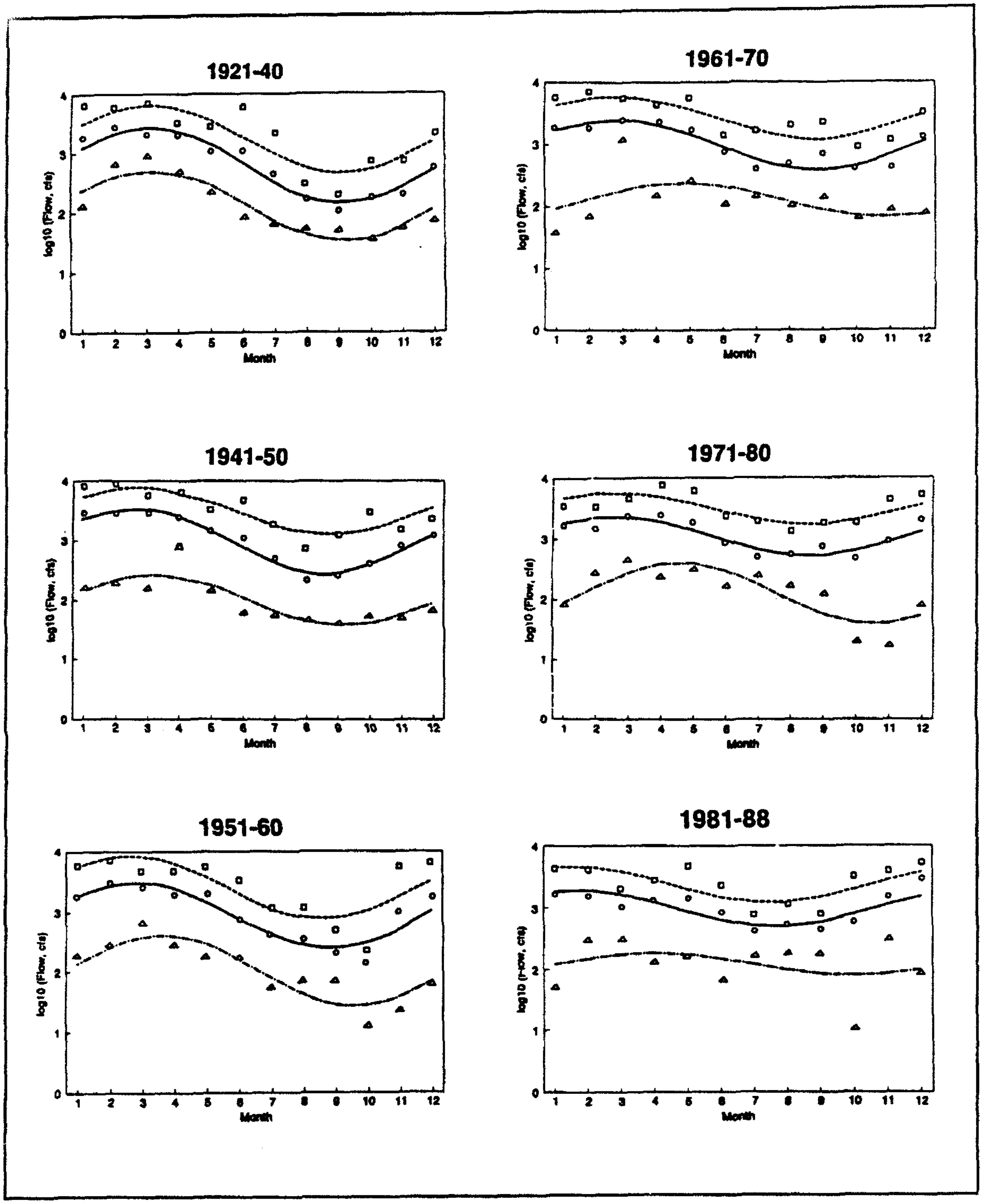


Figure 12. Harmonic analysis of the Cache River at Patterson, AR

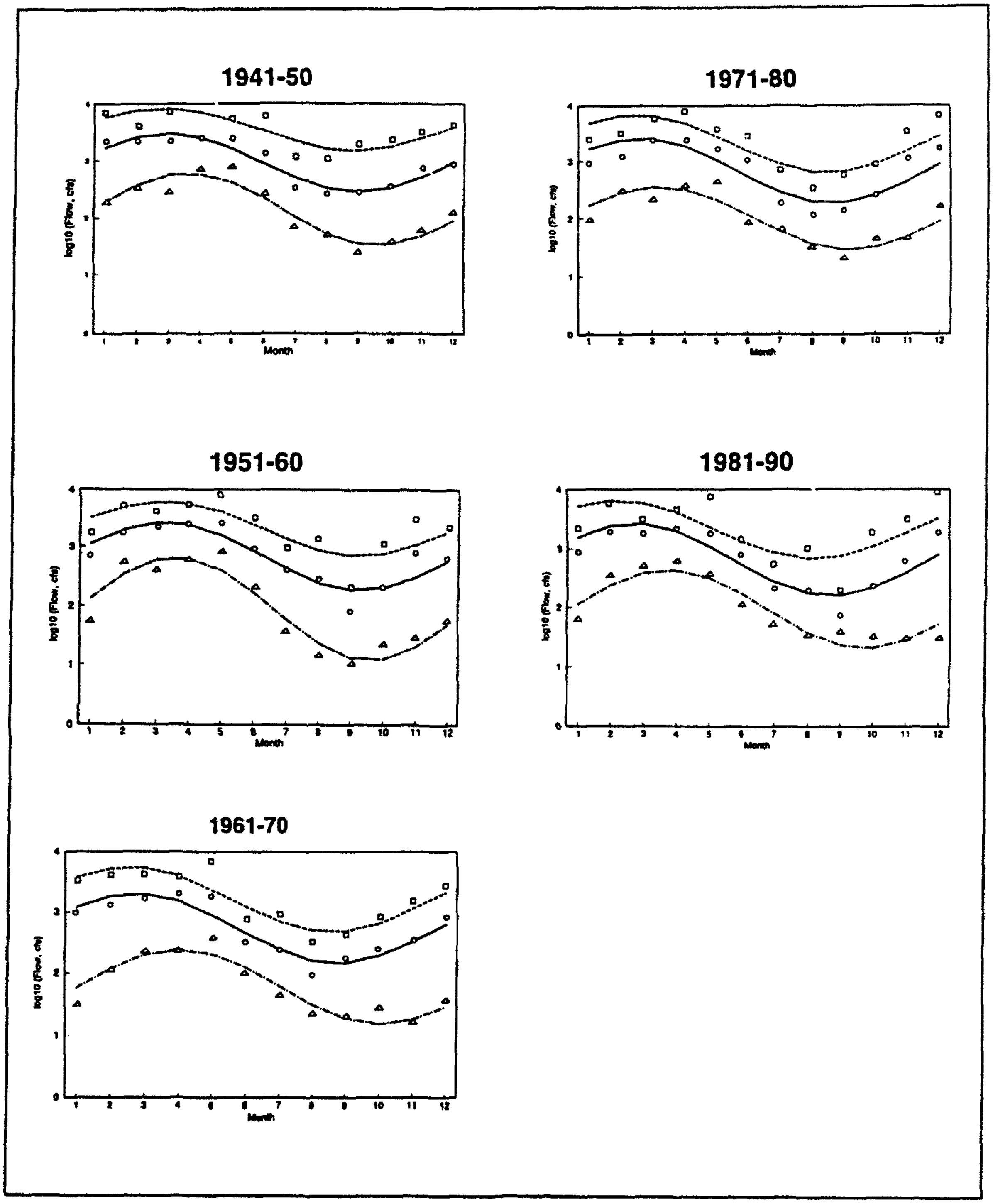


Figure 13. Harmonic analysis of the Buffalo River near St. Joe, AR

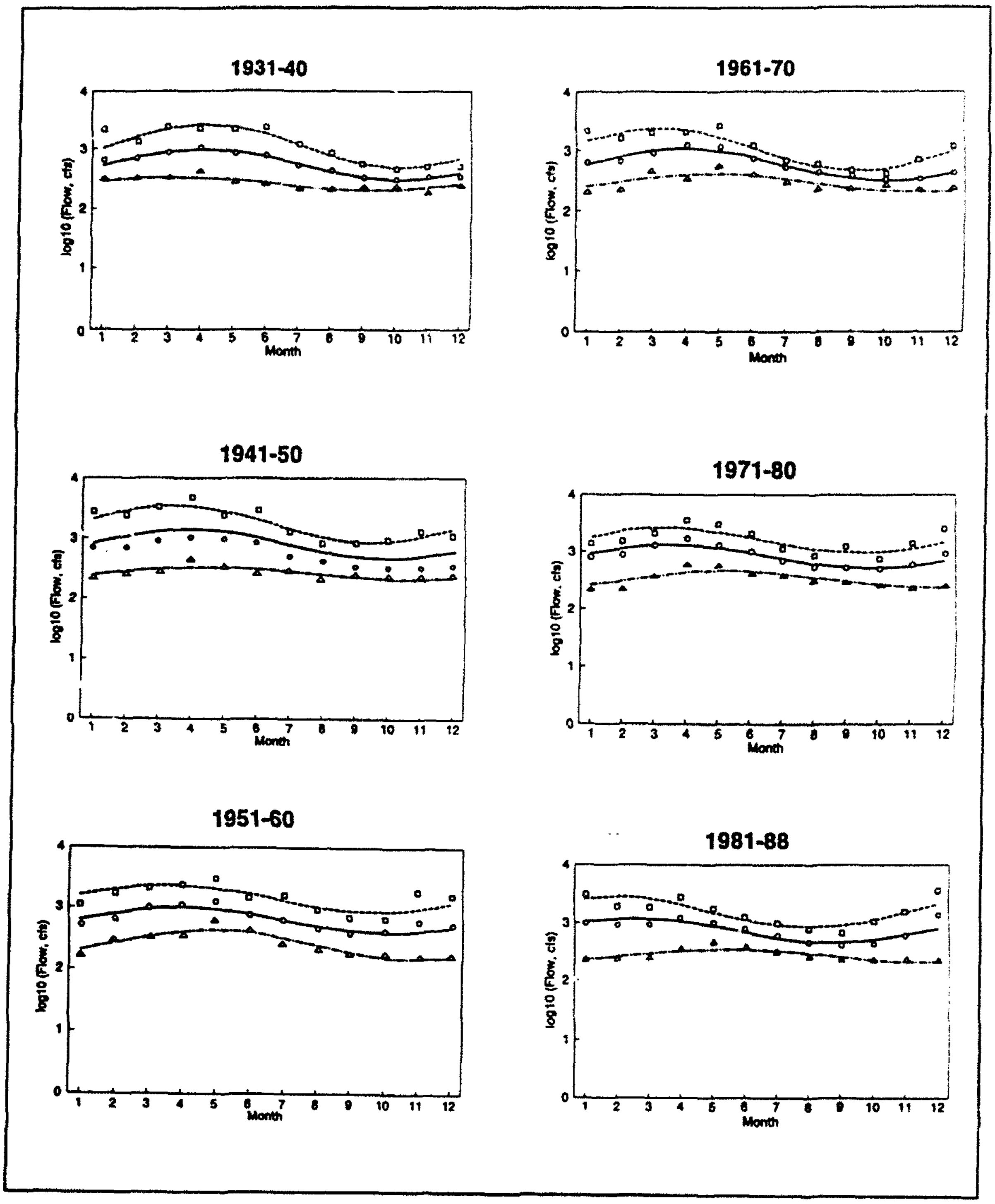
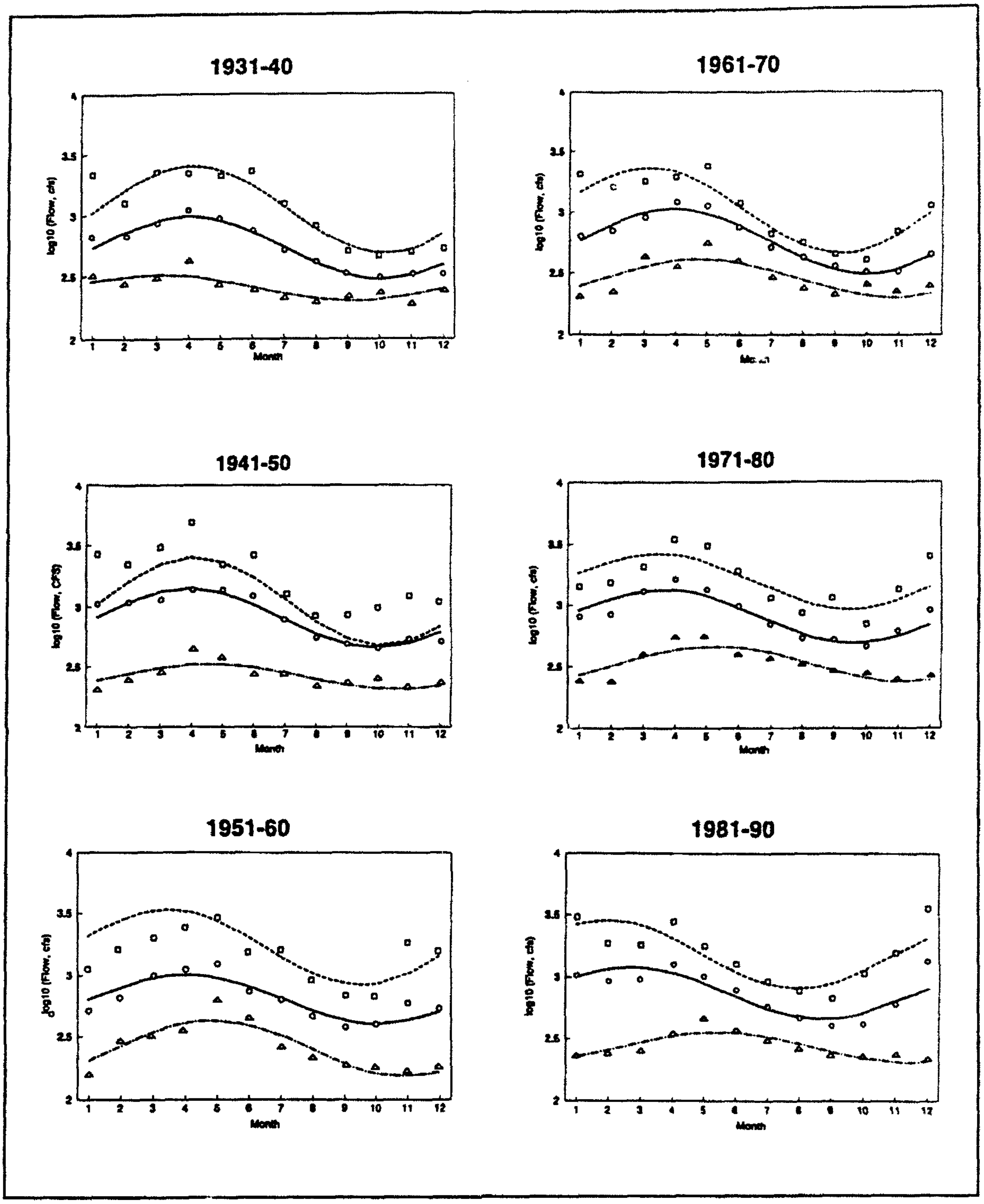


Figure 14. Harmonic analysis of the Eleven Point River near Bardley, MO, using two different scales (Continued)



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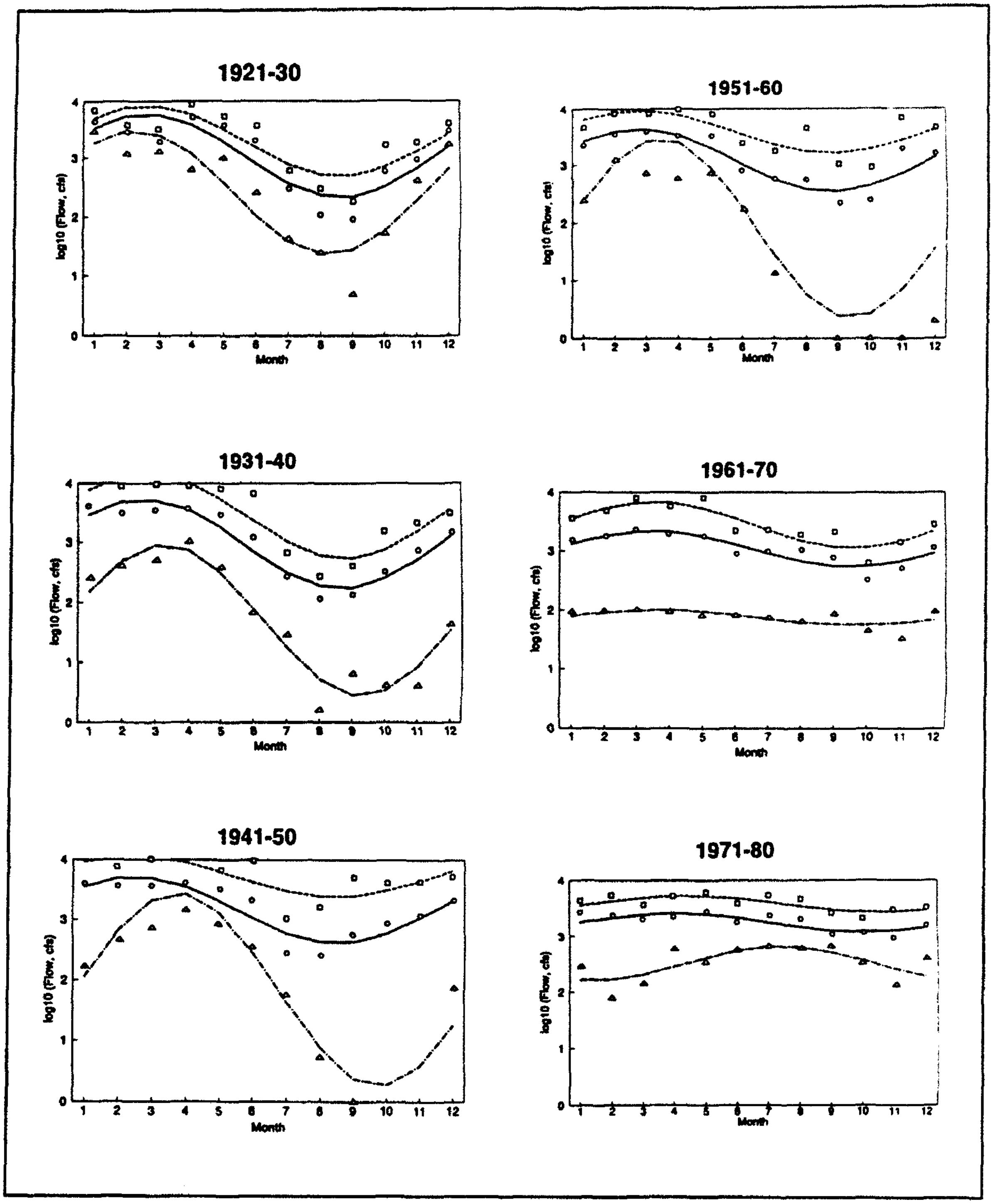

Figure 15. Harmonic analysis of the Little Red River near Heber Springs, AR

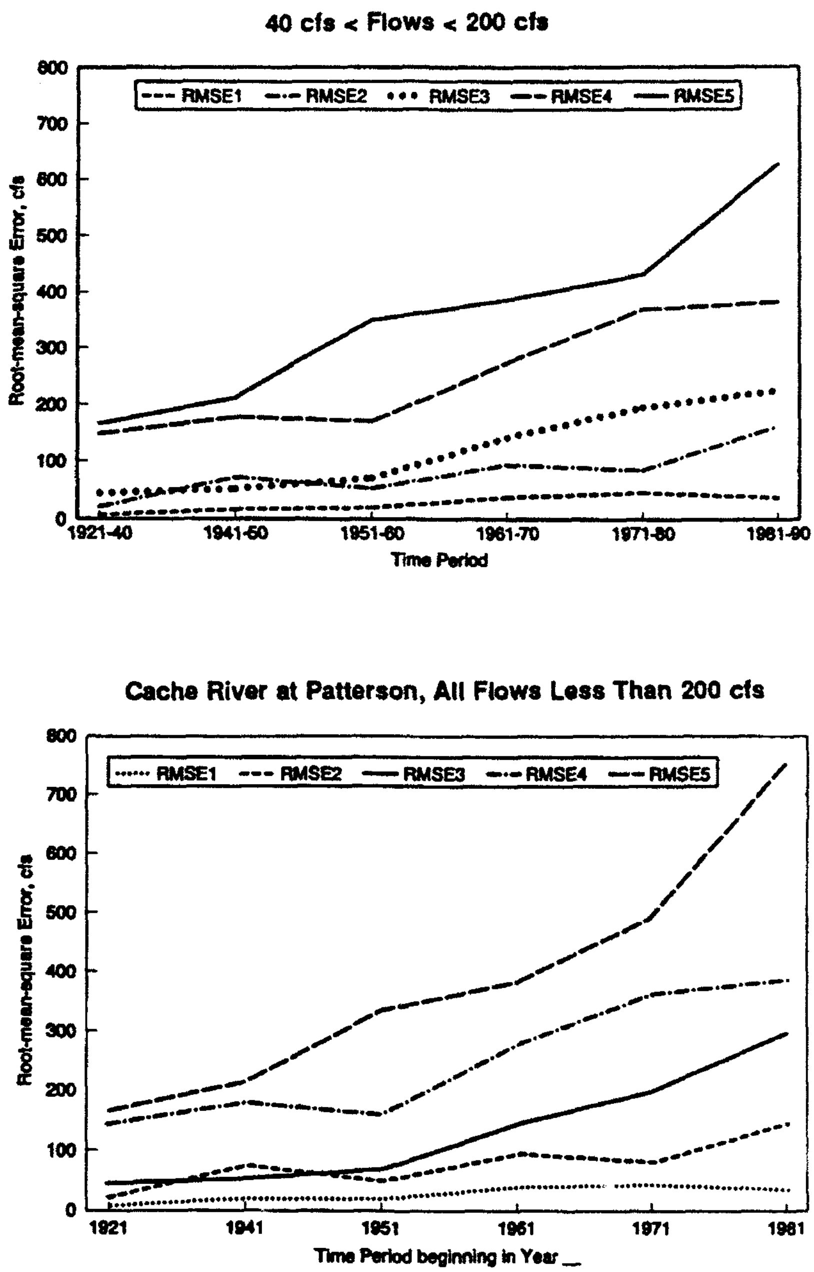

Figure 16. Root-mean-square error (RMSE) of flows of the Cache River at Patterson, AR, showing effects of different recording methods

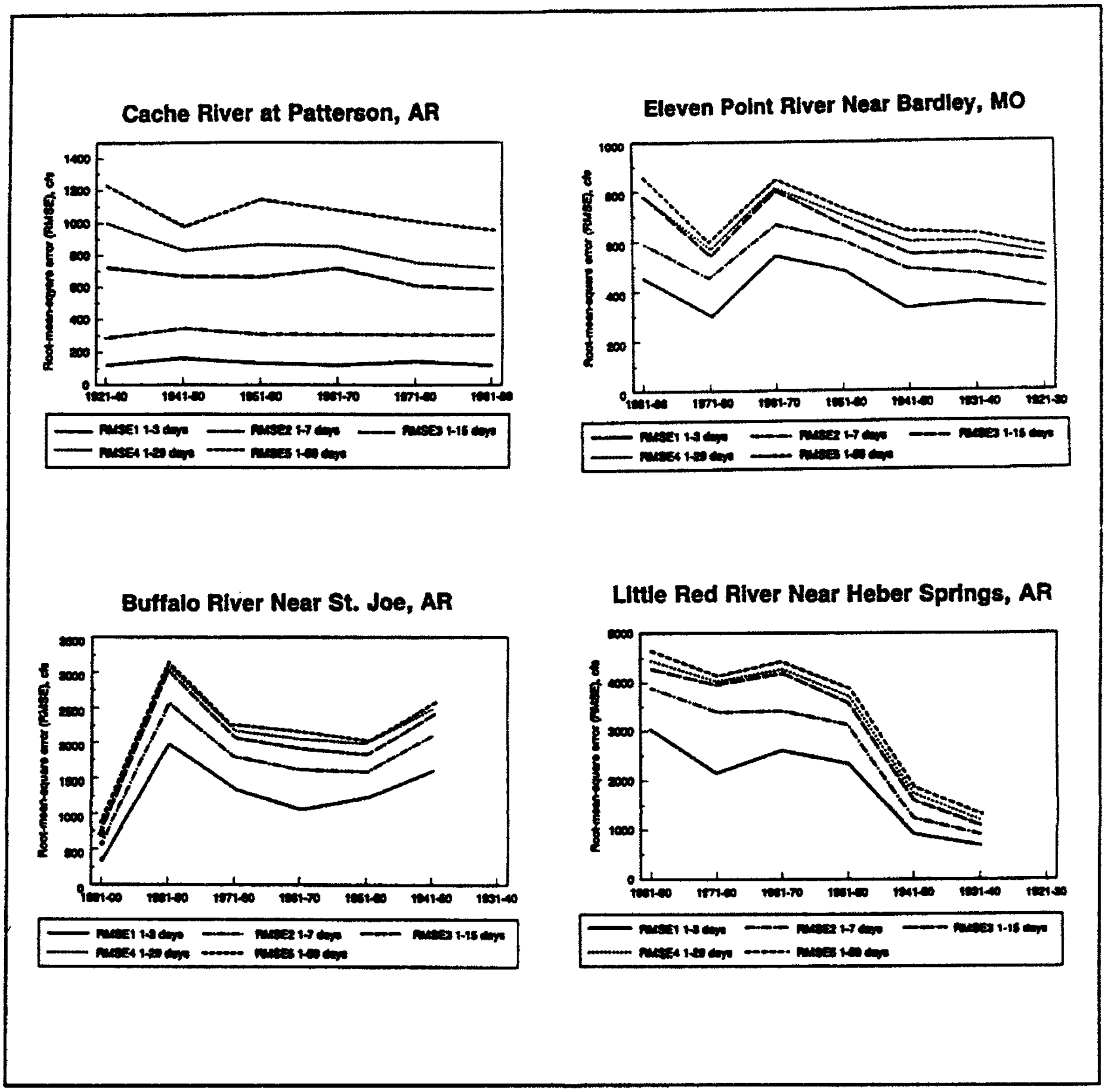

Figure 17. Comparison of respective root-mean-square errors (RMSE) of streams examined with time-scale analysis. All recorded flows are considered for each stream

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13. ABSTRACT *(Maximum 200 words)*

In order to make informed decisions concerning cumulative impact analysis of wetlands, the Corps of Engineers Districts and other wetlands professionals need data often not directly available. Cumulative impact assessment of wetlands includes relating historic patterns of flow, derived from the stream's flow record, to changes in the watershed associated with that stream. Harmonic analysis and time-scale analysis were applied to selected stream records to ascertain their potential for describing cumulative impacts.

The study area chosen included selected streams in the White River basin, Arkansas/Missouri. The Cache River received particular emphasis because a significant amount of information was readily available concerning it and its surroundings. Daily flow values were retrieved from each of the streams. Using non-linear, harmonic analysis as well as time-scale analysis (a technique adapted from fractal geometry) to reveal the time-dependent patterns in the respective samples, the results were compared decade-by-decade to discern changes in the historic, seasonal patterns. Other streams in the White River basin were analyzed in the same manner and compared with the Cache River, noting historic changes in land use and stream regulation.

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13. (Concluded).

The study identifies methods with the potential to differentiate historic time frames in which disruptions were likely to have occurred. The methods appear to be translatable to other geographic areas where streamflow is typically seasonal.

14. (Concluded)

Cache River	Cumulative impact assessment
Daily values	Environmental impact
Harmonic analysis	Hydrology
Nonlinear regression	Root-mean-square error
Streamflow	Time-scale analysis
White River	